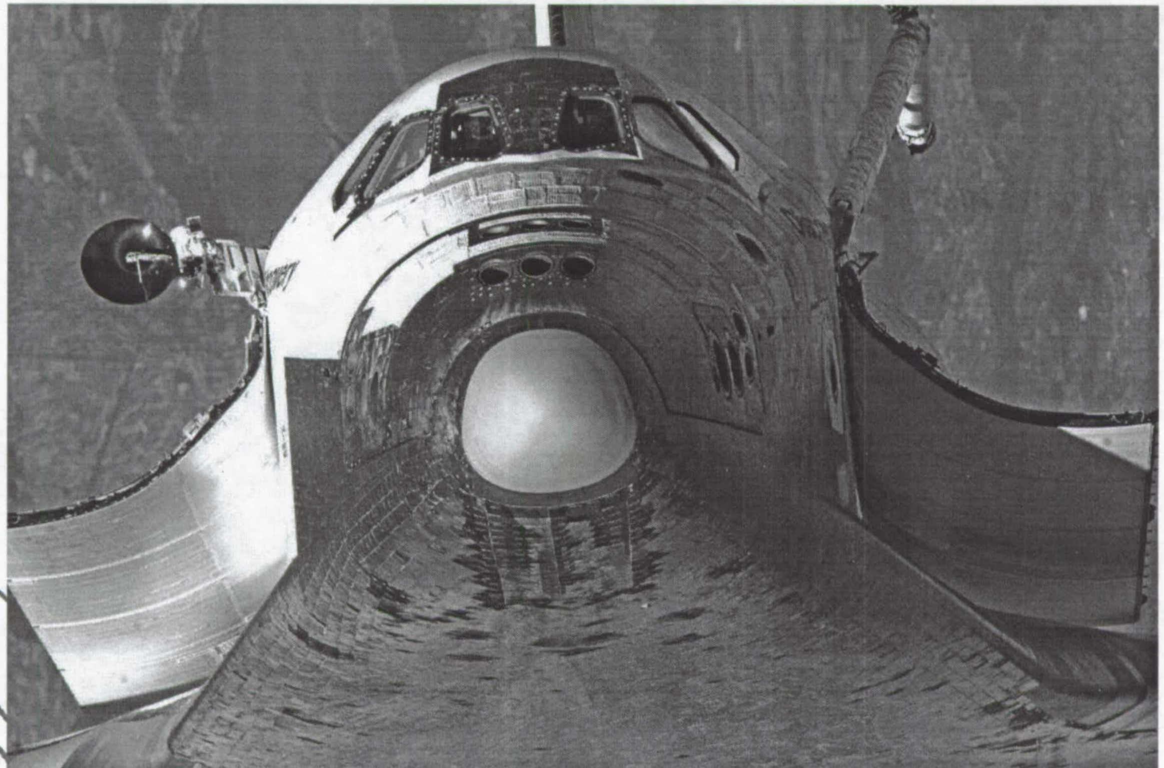
The Space Shuttle Columbia: A Materials Forensic Analysis

MICROSCOPY 2007



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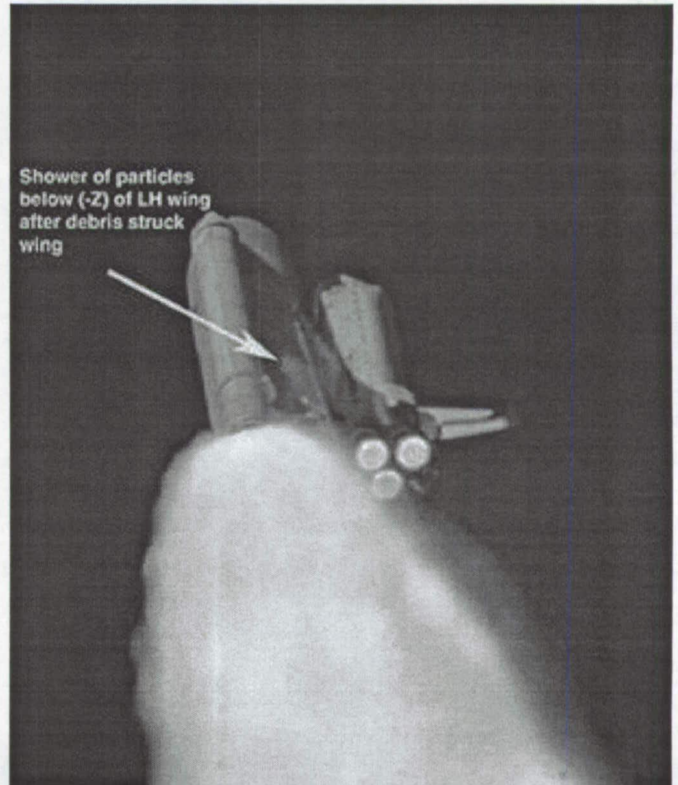
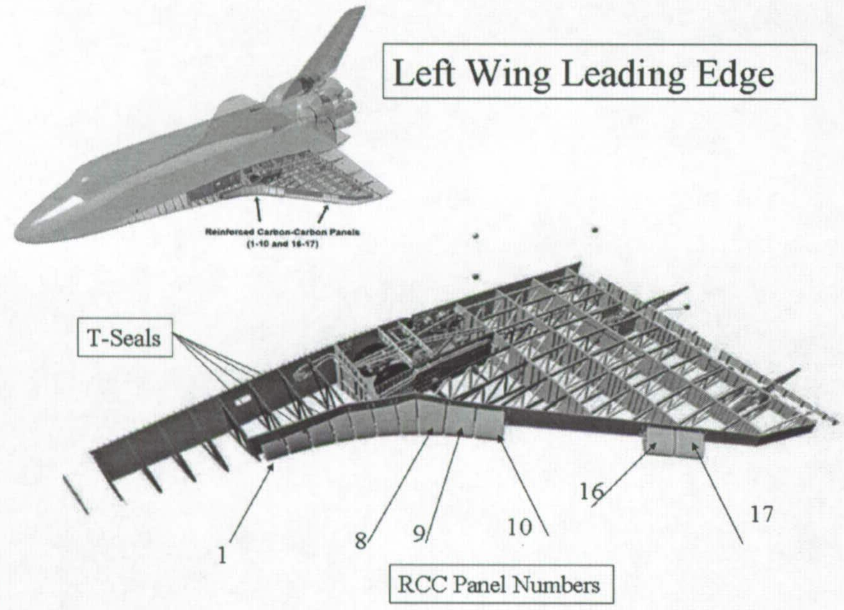
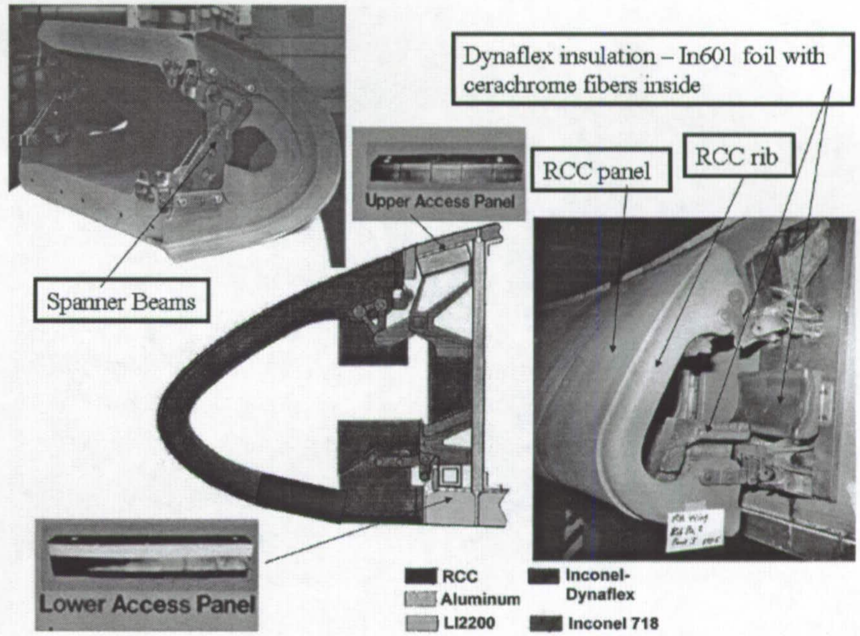
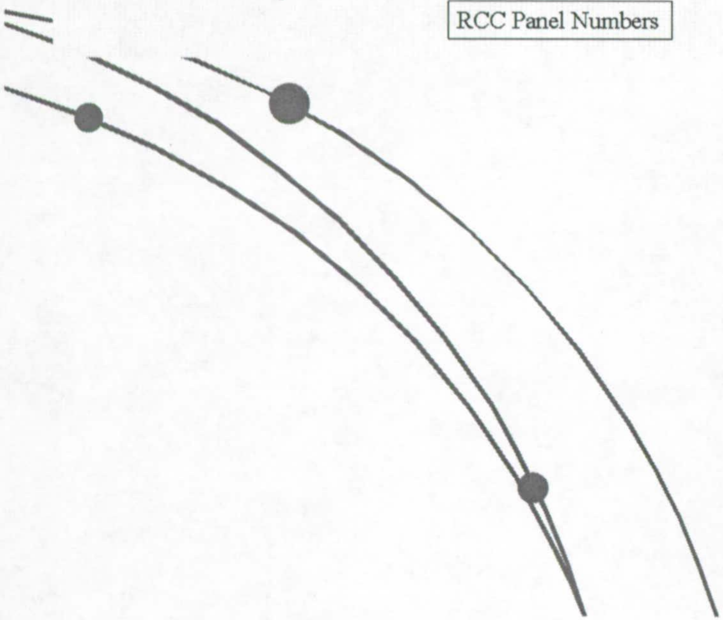
Shuttle Columbia: STS-107

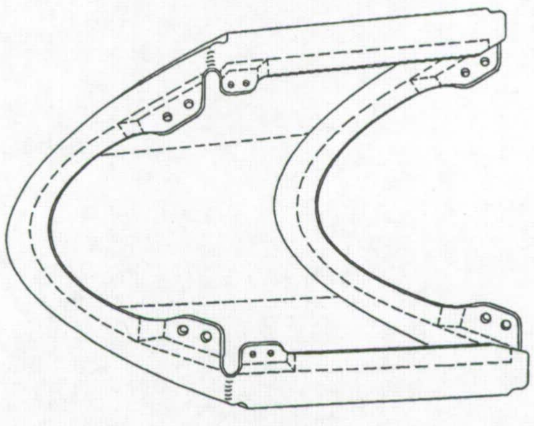


Leading Edge Representation

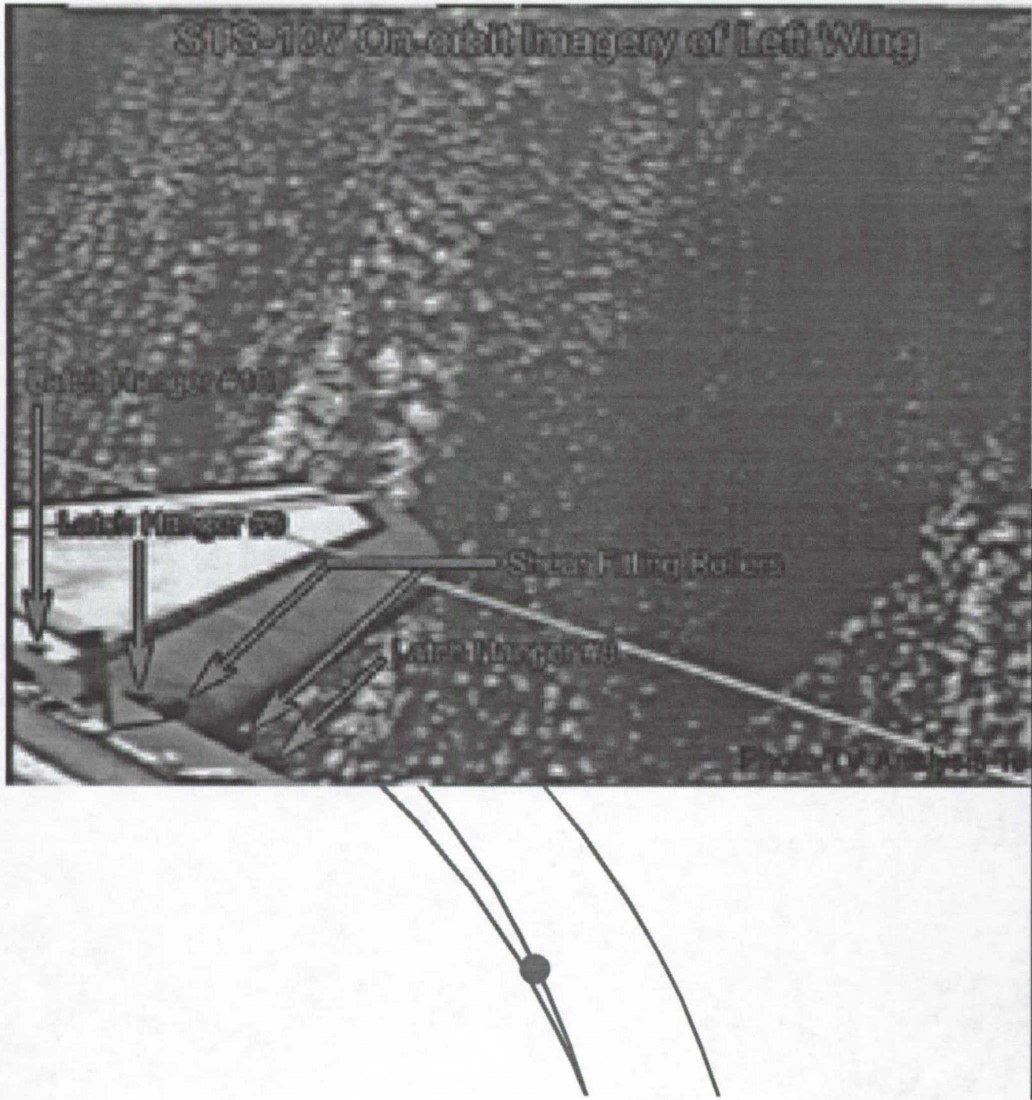


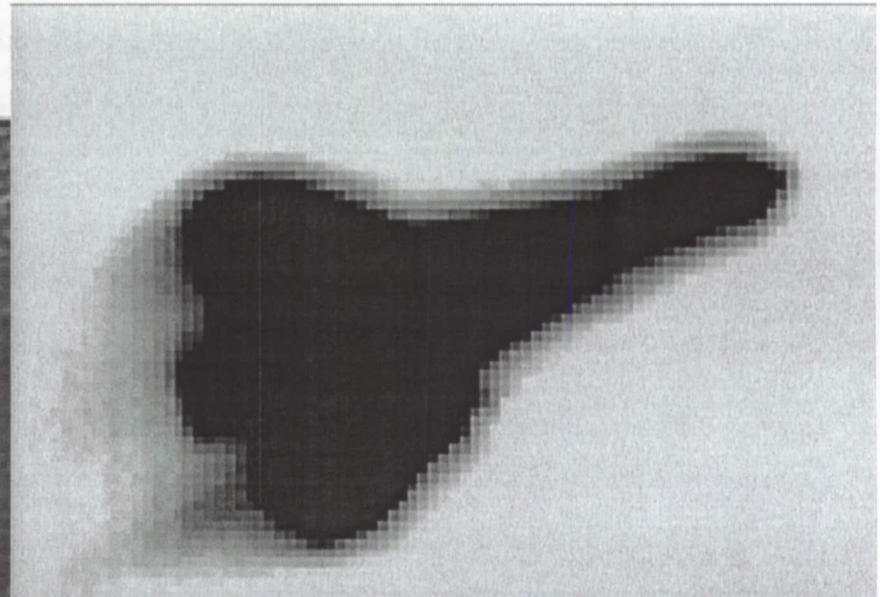


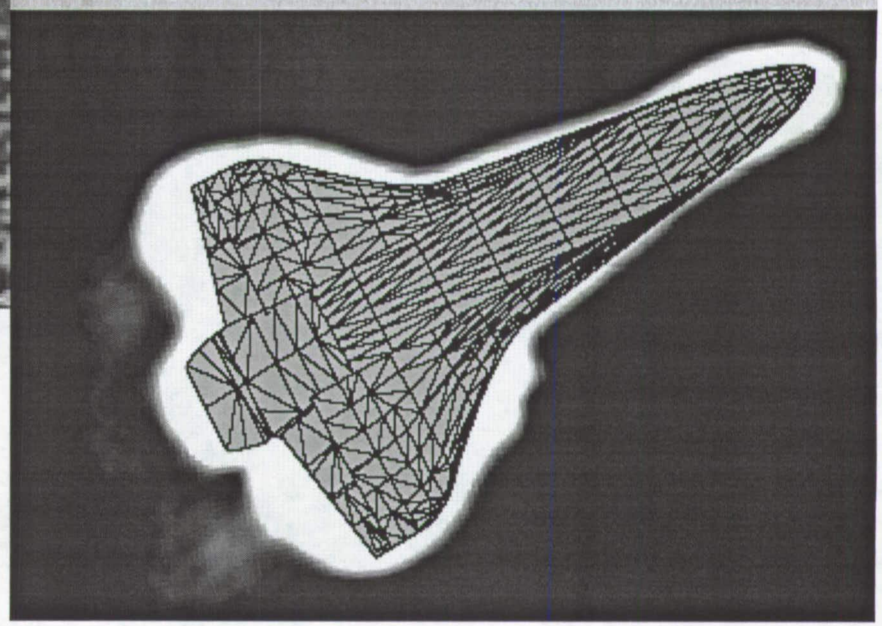




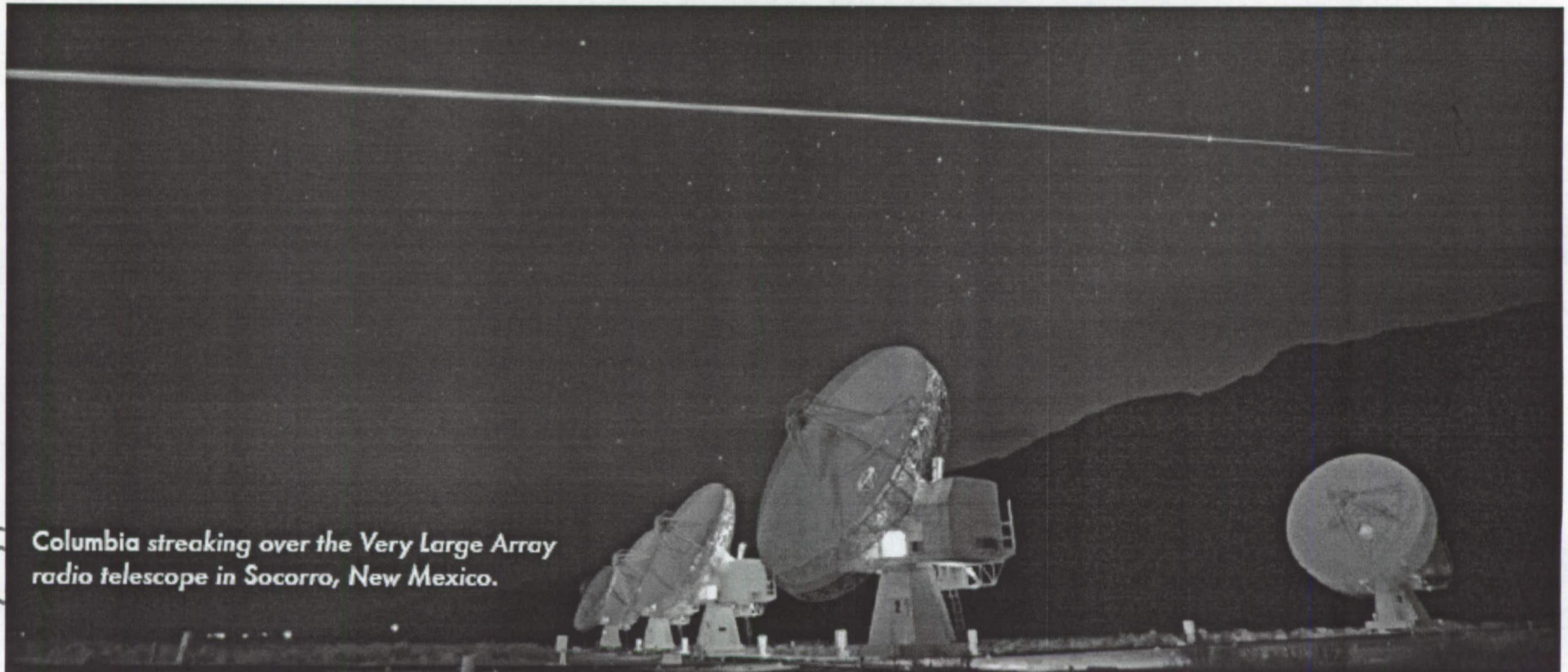
Columbia Imagery



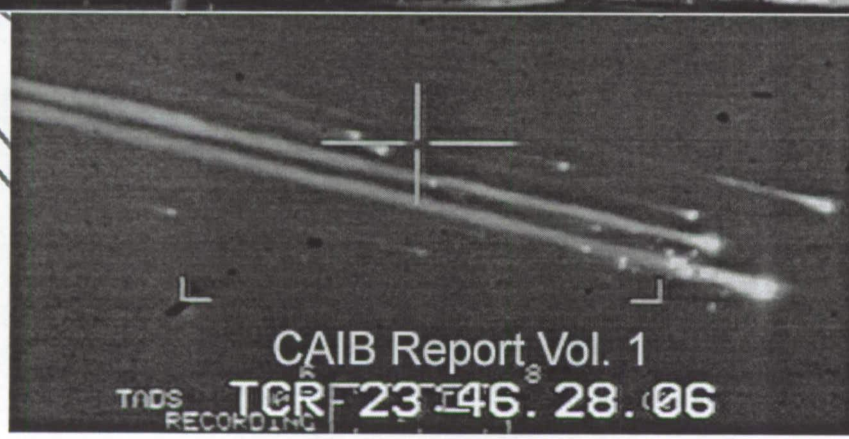




Columbia During Re-Entry

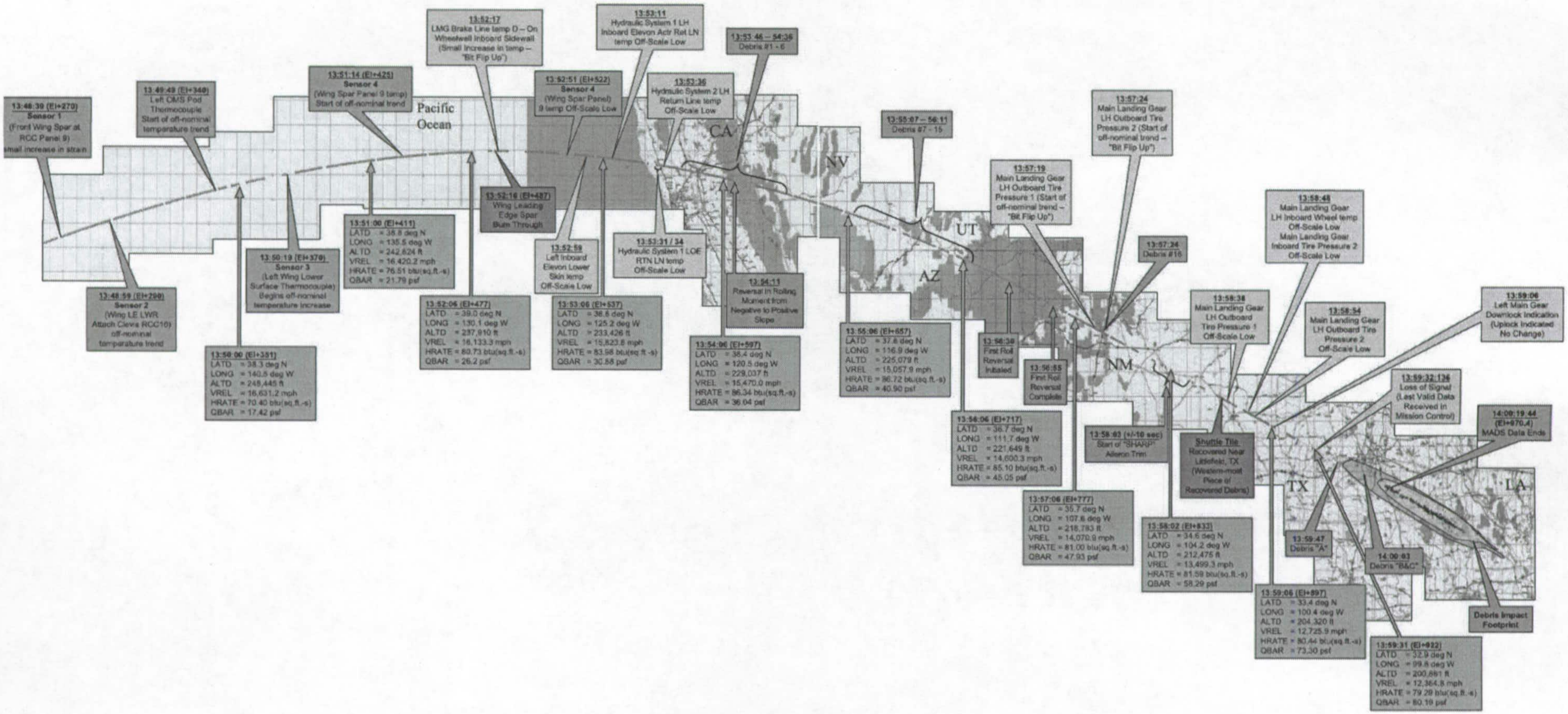


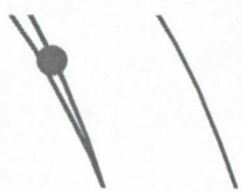
Columbia *streaking over the Very Large Array radio telescope in Socorro, New Mexico.*



CAIB Report Vol. 1

STS-107 Timeline

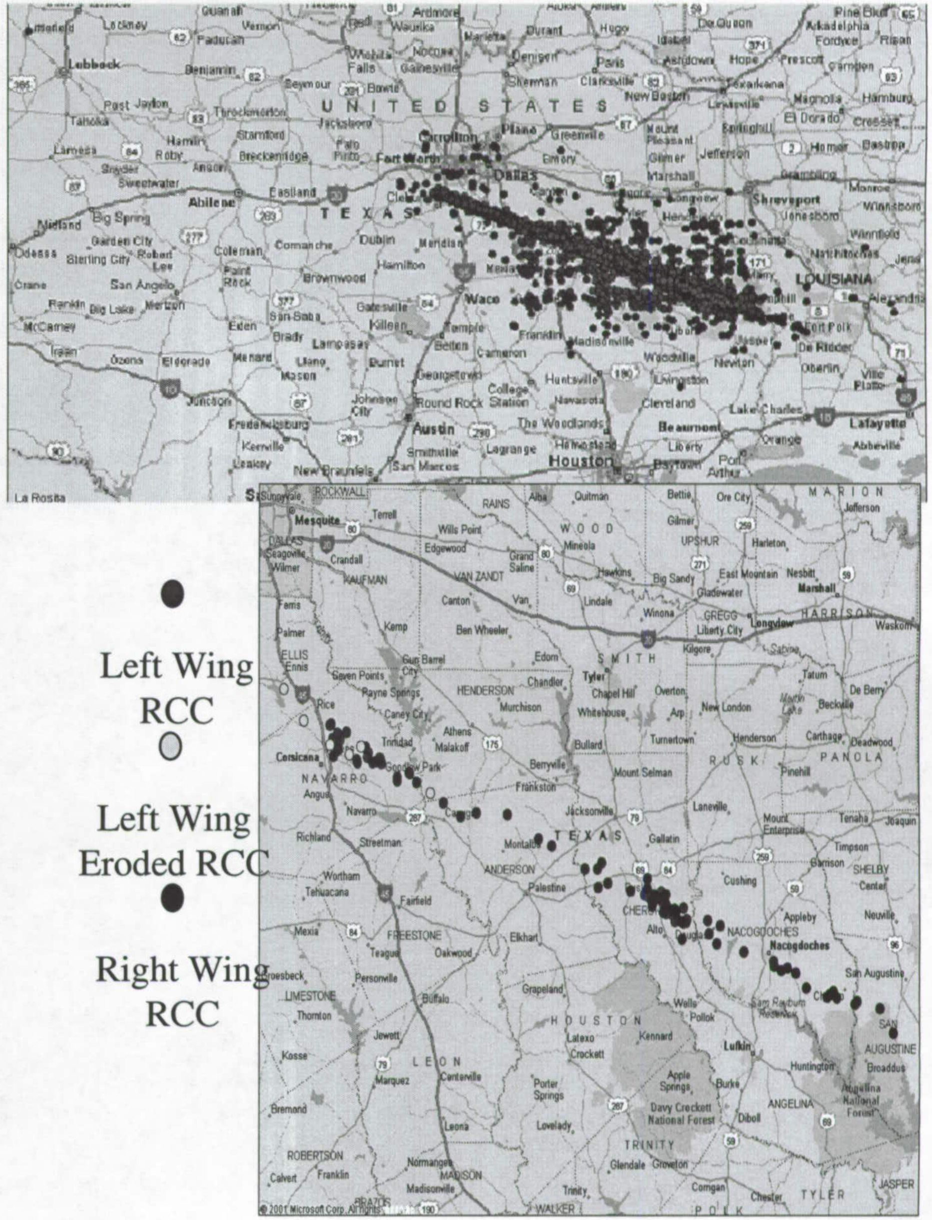




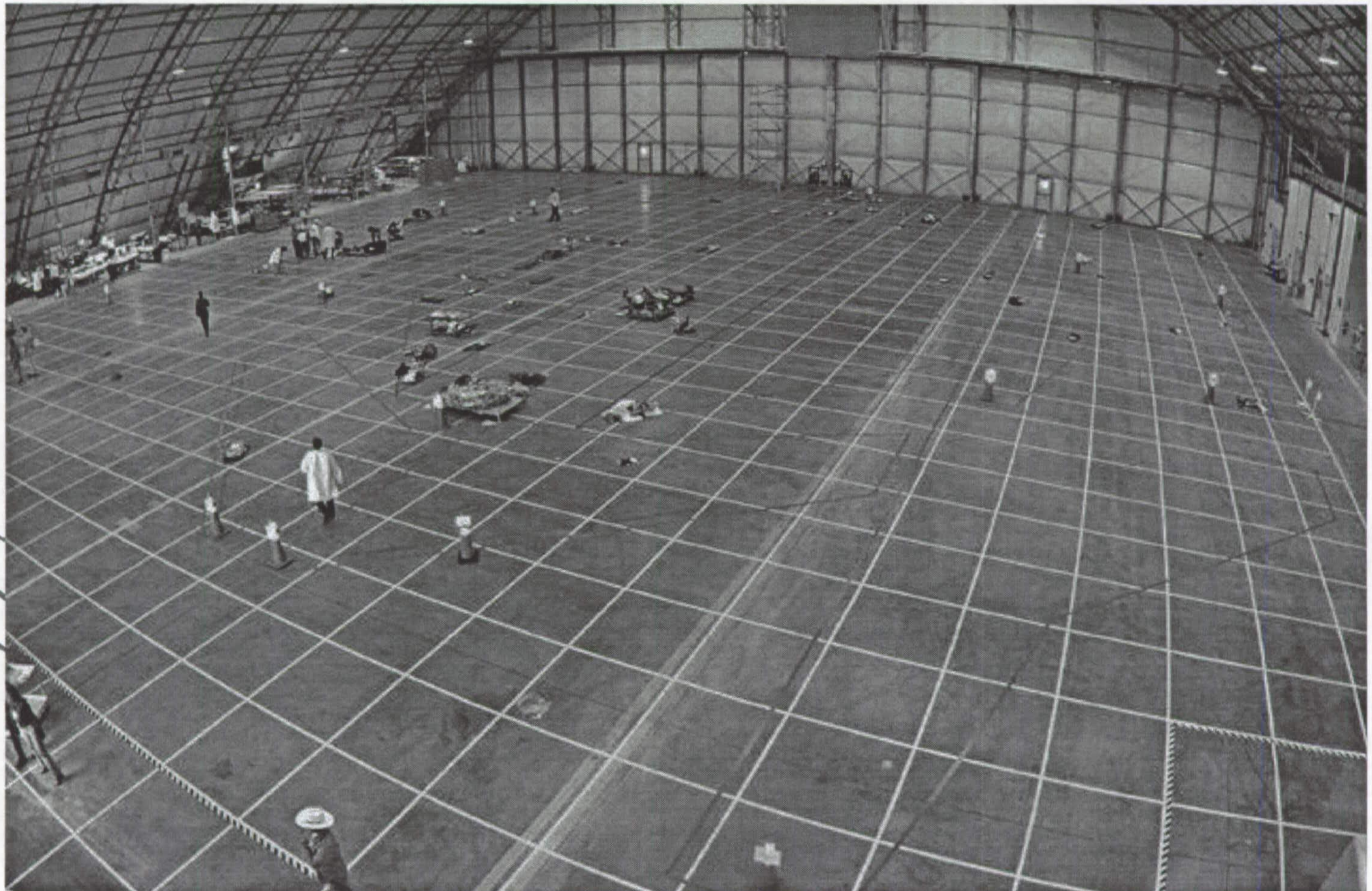
Columbia Recovery and Reconstruction

Recovery

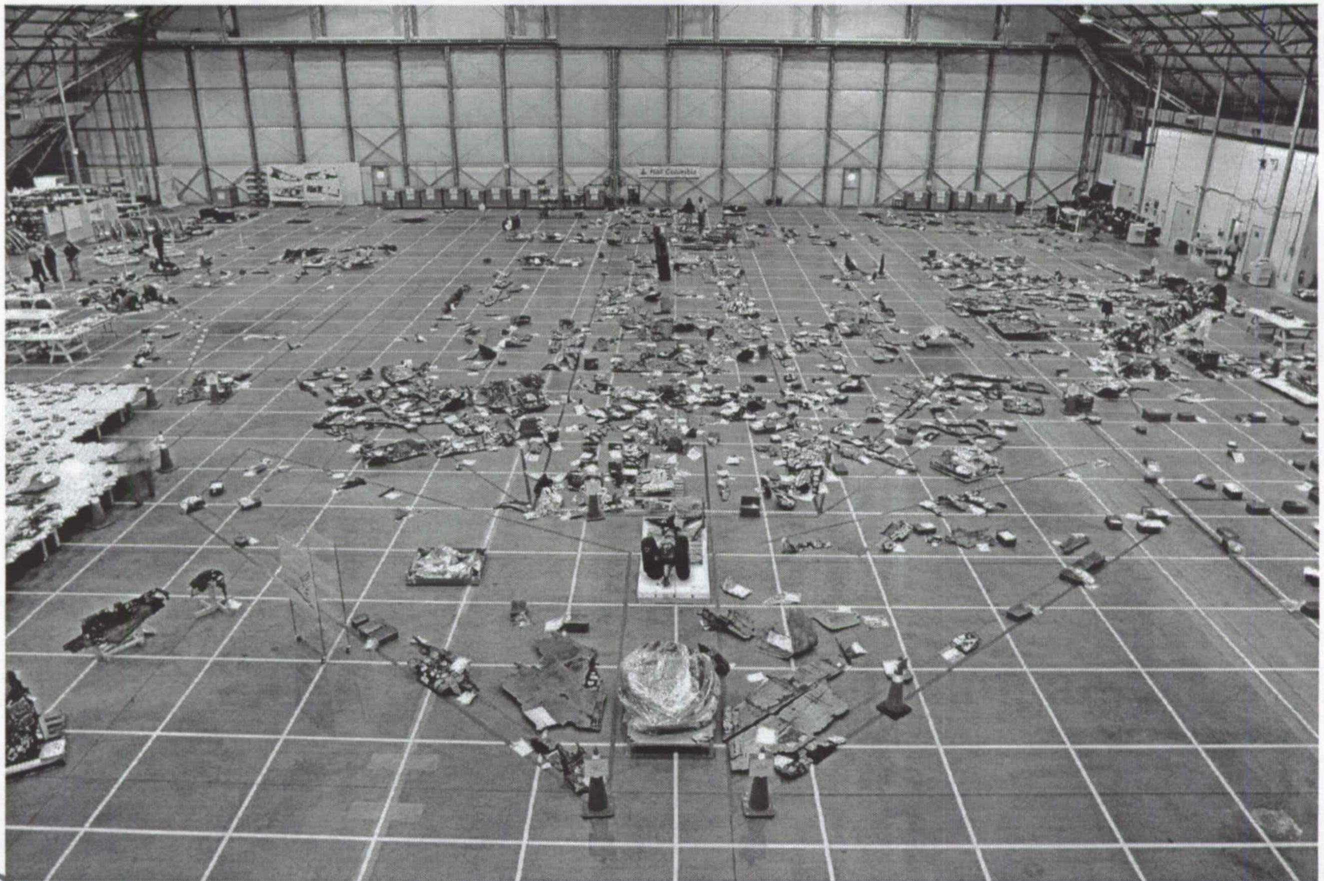
- Columbia was traveling at Mach 18 at an altitude of 208,000 feet/63 KM at time of break-up
- The size of the debris field was 645 miles/1,038 KM long and 10 miles/16 KM wide
- 16,000 volunteers expended 1.5 million hours
- Approximately 84,000 pieces retrieved, weighing approximately 85,000 pounds/38,555 kg (roughly 38% of the Orbiter's dry weight)
- Debris Reconstruction Team at KSC – 150 people 150,000 hours expended in reconstruction phase



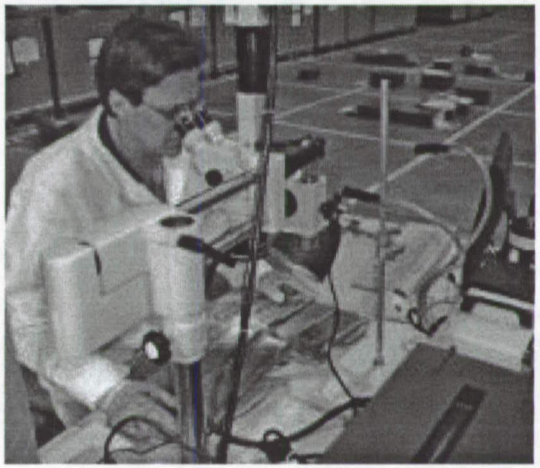
Reconstruction Hangar: 2-14-03



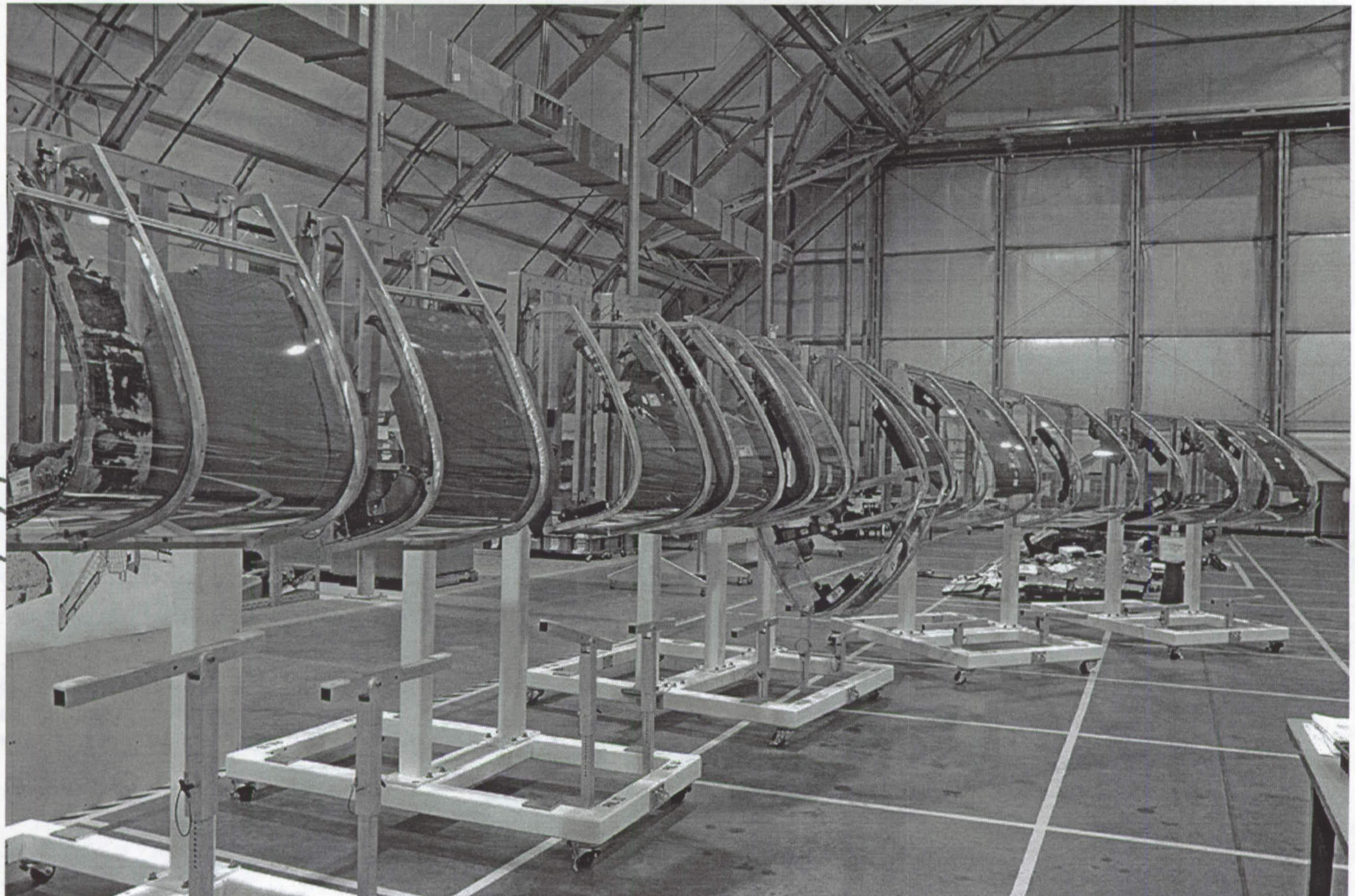
STS-107 Reconstruction Hangar



Initially, analysis was restricted to visual and macroscopic examination of debris in the hangar.

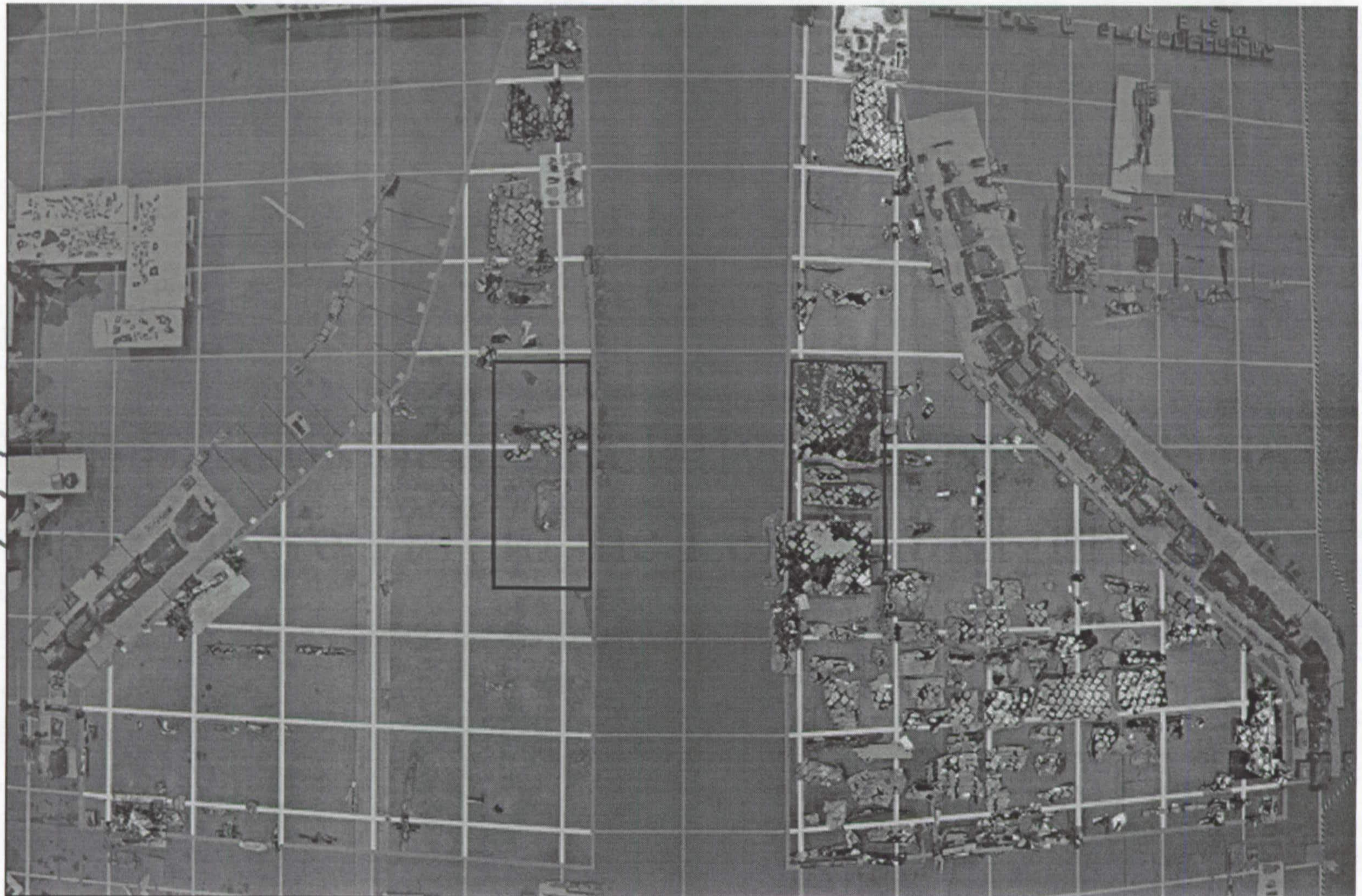


Three-Dimensional Reconstruction Of Left Hand Leading Edge



Reconstruction: Right Wing

Comparison of the Relative Amount of Debris Recovered From the Left and Right Sides

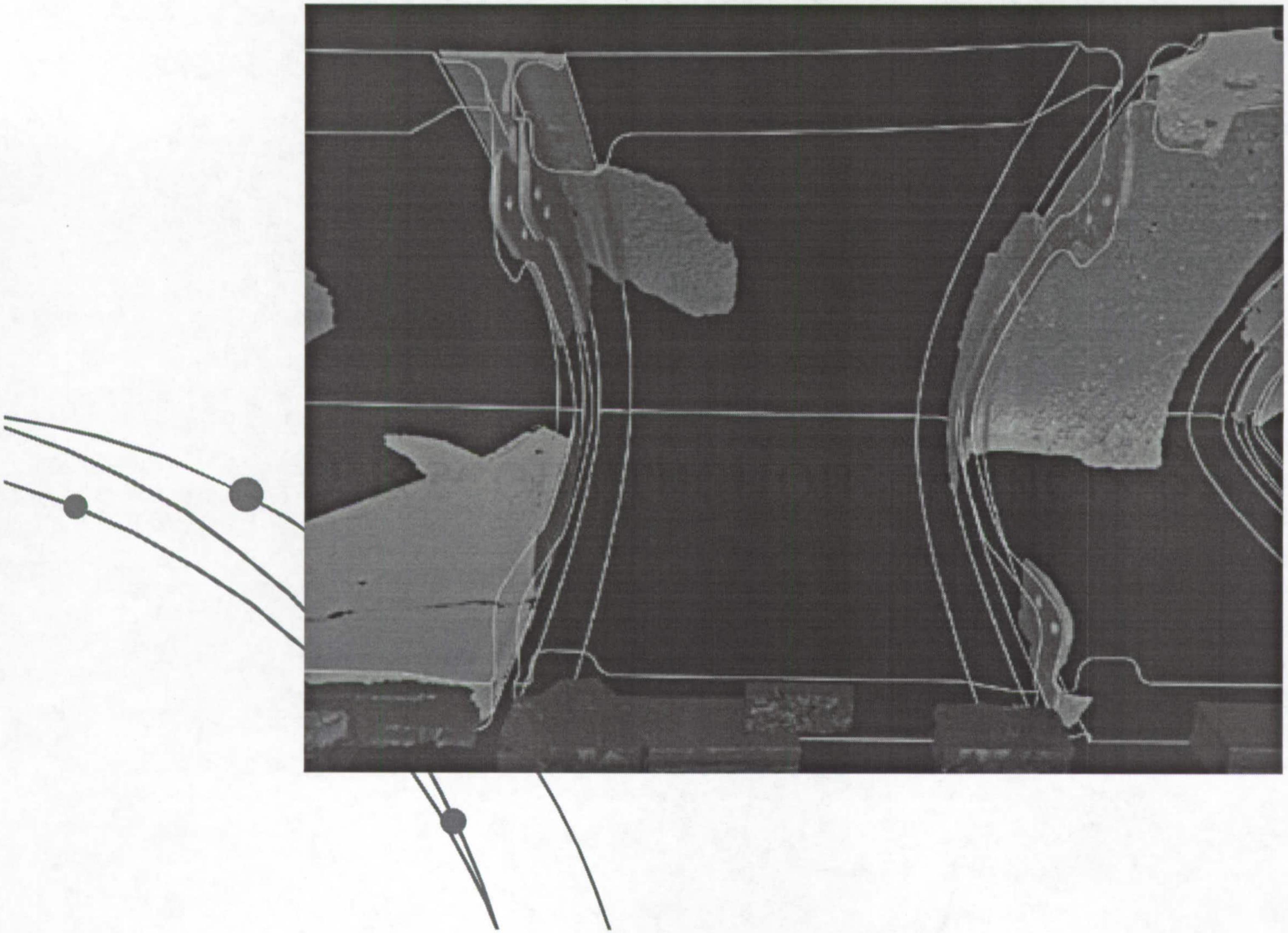


Reconstruction: Tiles

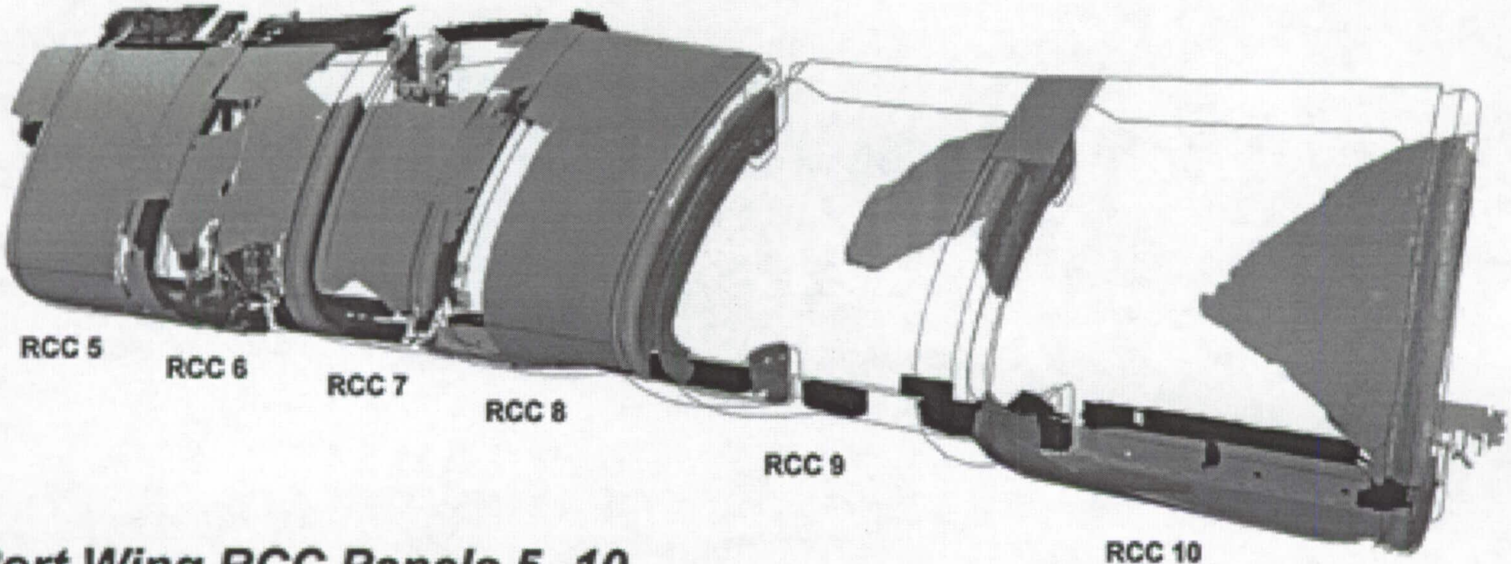
Reconstruction

Reconstruction: From Left Wing

3D Reconstruction: Panels 8, 9, 10



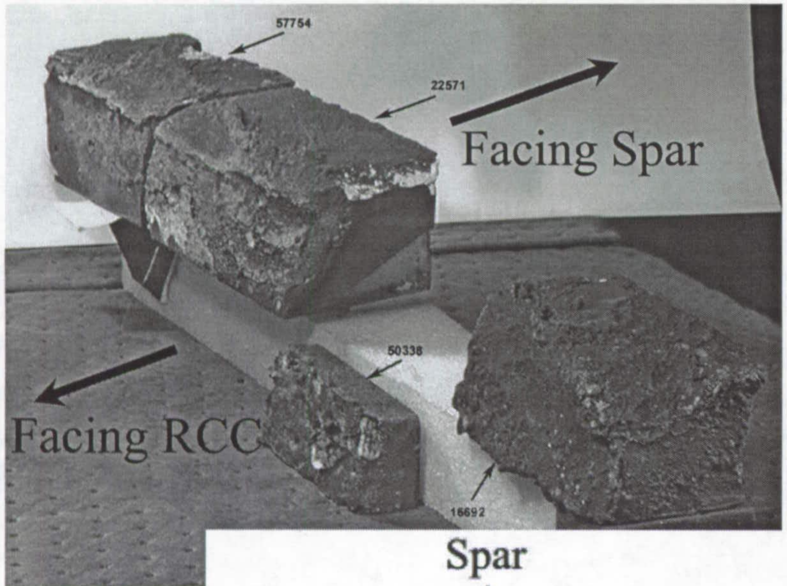
3D Reconstruction

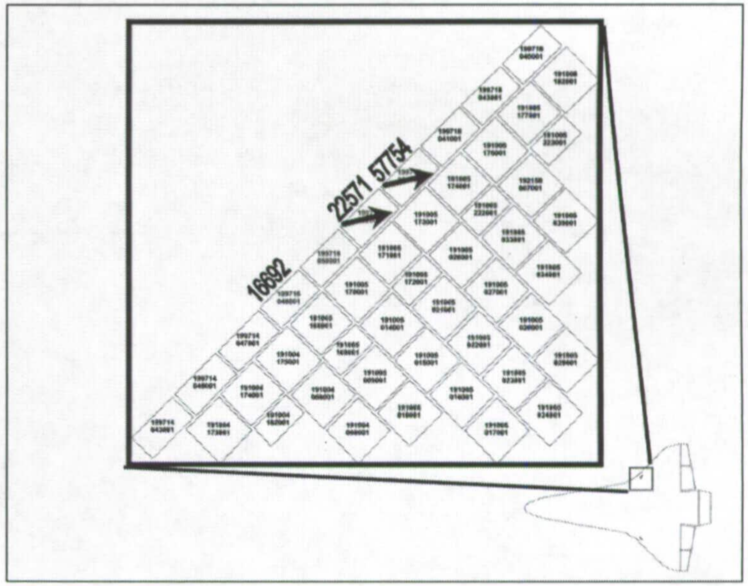


Port Wing RCC Panels 5 -10

3D Virtual Reconstruction of Left Wing

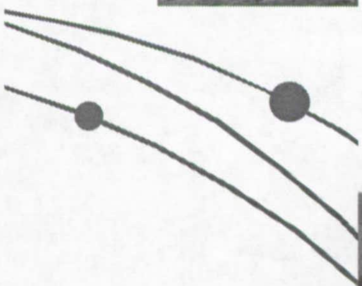
Patterns





Spar

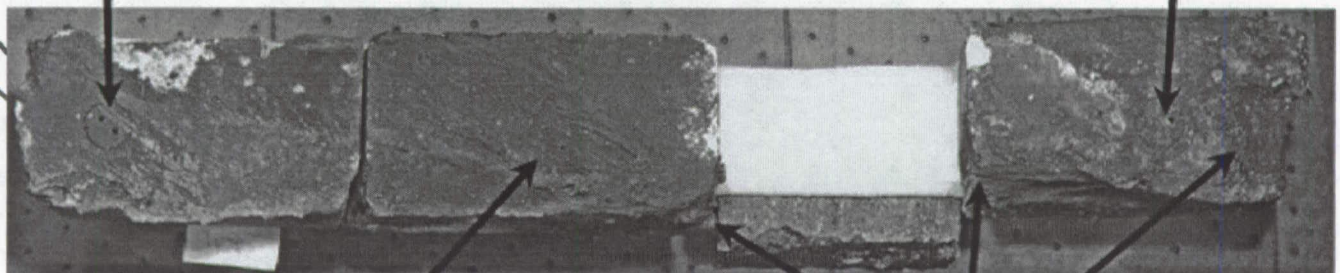
RCC



Plug/Insert

View Looking up

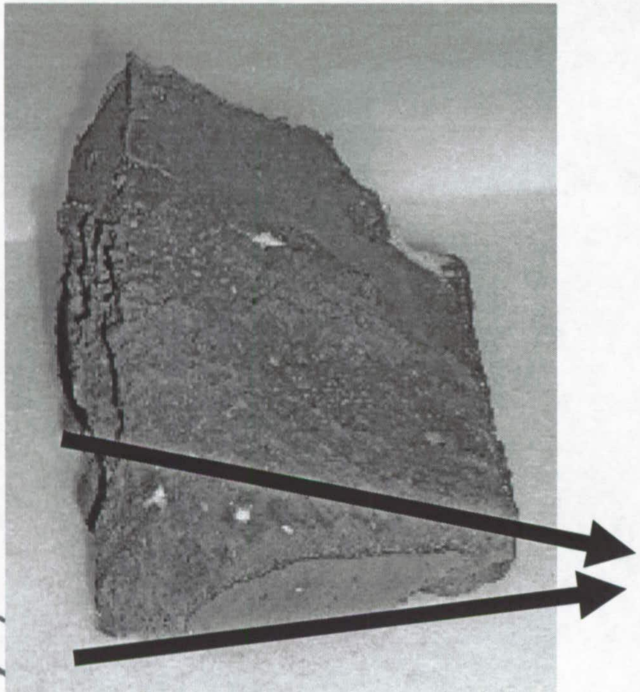
Plug/Insert

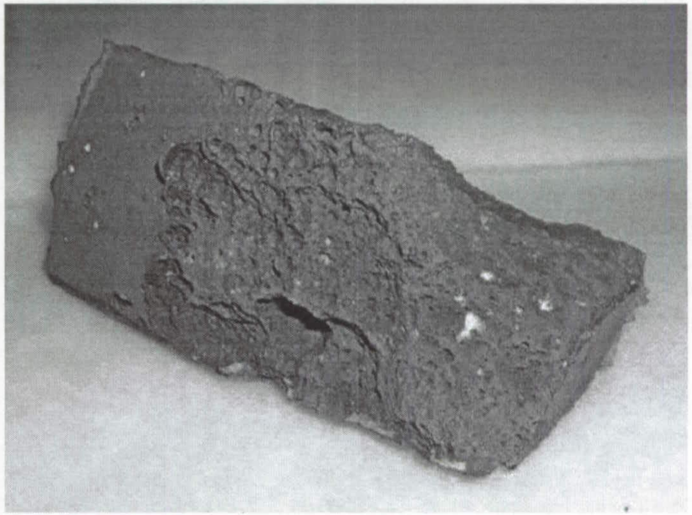


"Slag" deposits

Depressed/eroded regions

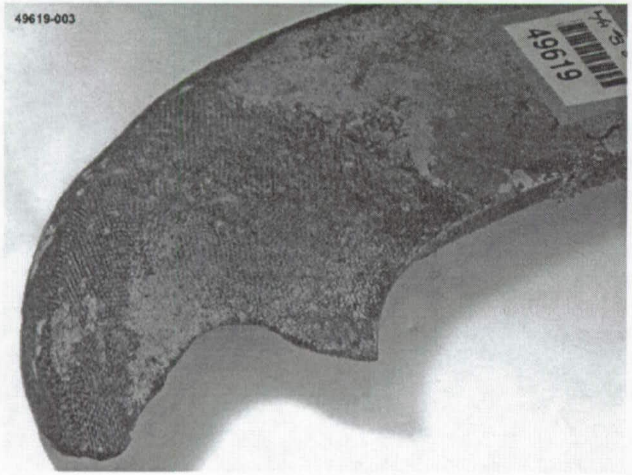
Carrier Panel 8 - Upper



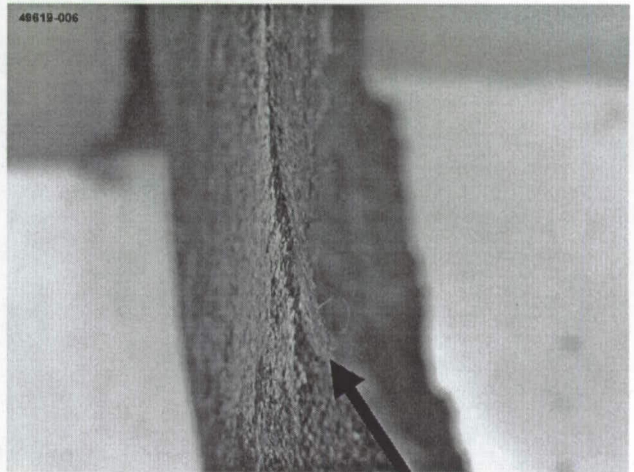


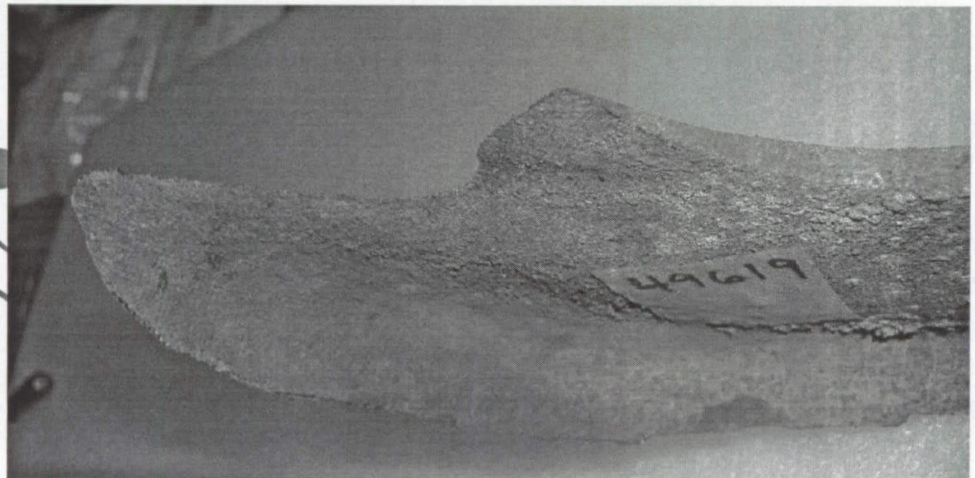
Slumping and erosion patterns suggest plasma flow out of leading edge cavity (consistent with vent)

Erosion on Panel 8 Upper Outboard Rib



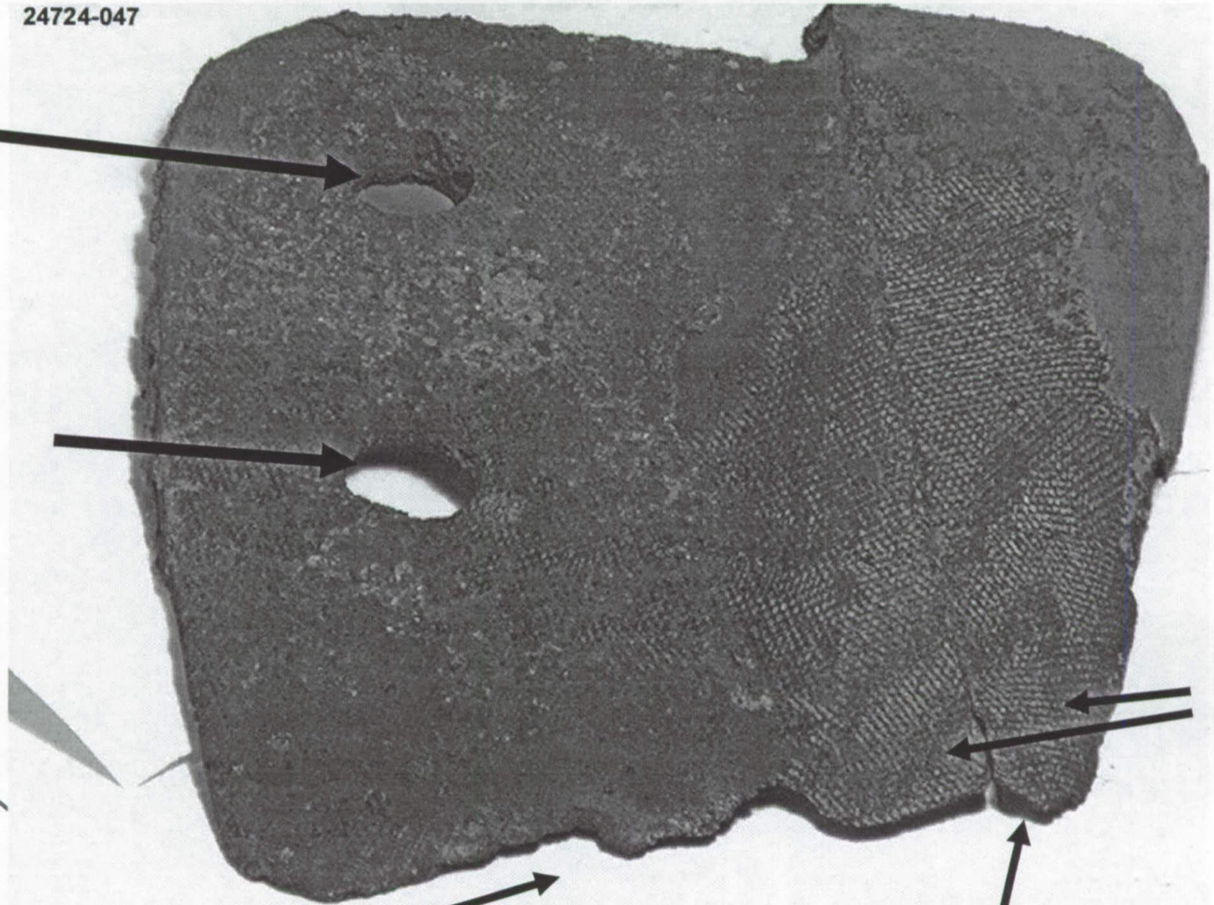
Outboard apex





Rib tapers from design thickness of .365” to .05”.

Erosion on Gap Surfaces of Panel 8 Outboard Lug & Matching Heel Piece



Heavy deposits in holes

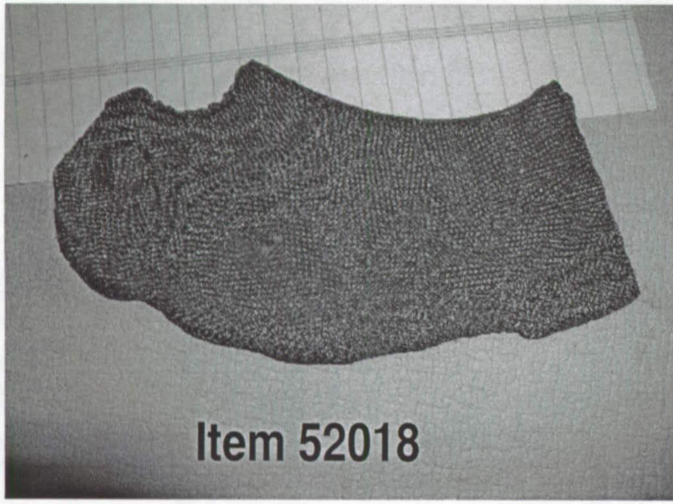
Inconel bushings missing, yet attach holes still intact

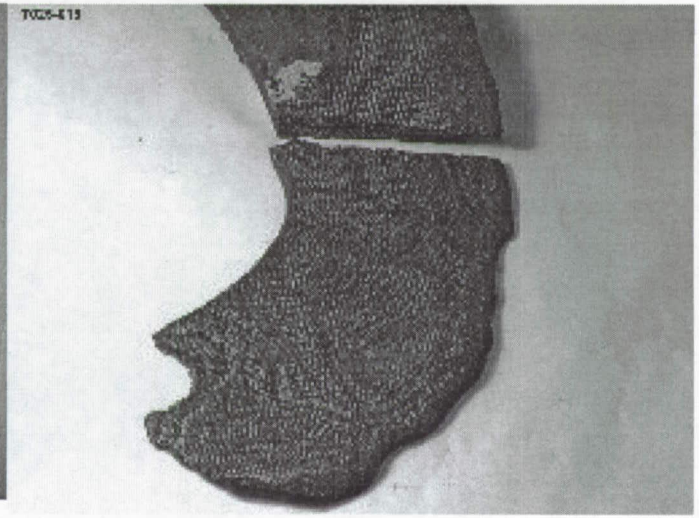
Matching eroded plies

Lug fragment tapers from .499"to a min knife edge of 0.063"

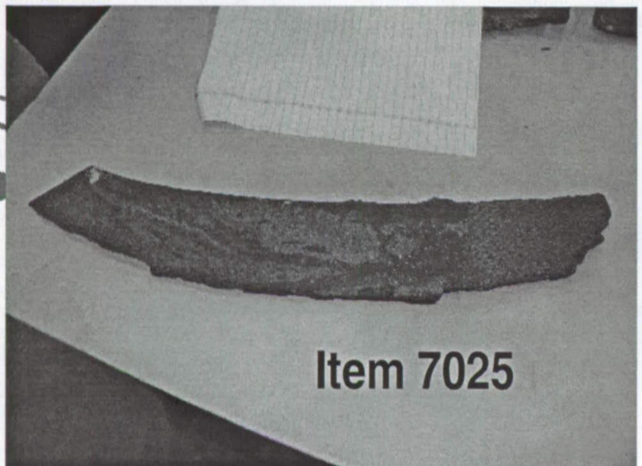
Heel fragment tapers from .233" to a min knife edge of 0.052"

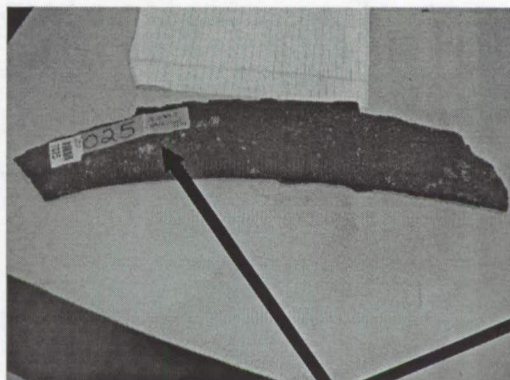
Erosion on Panel 9 Upper Inboard Rib





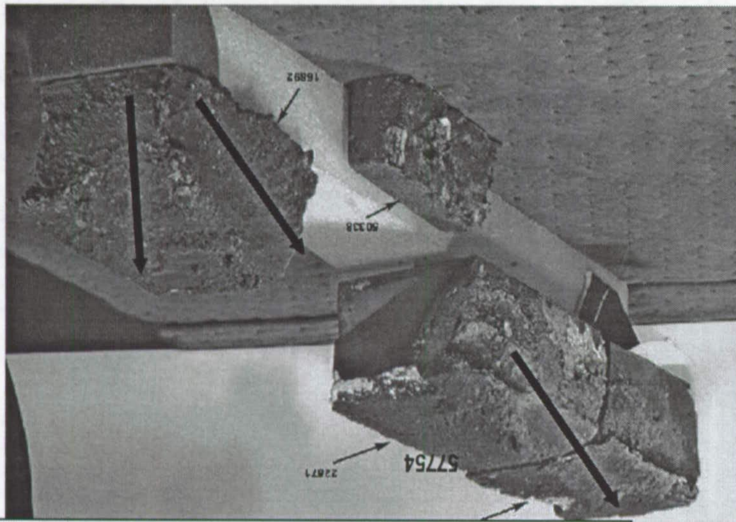
7025 to 52018 interface shows severe thermal erosion – thickness ranges from 0.270 to knife edge of 0.040



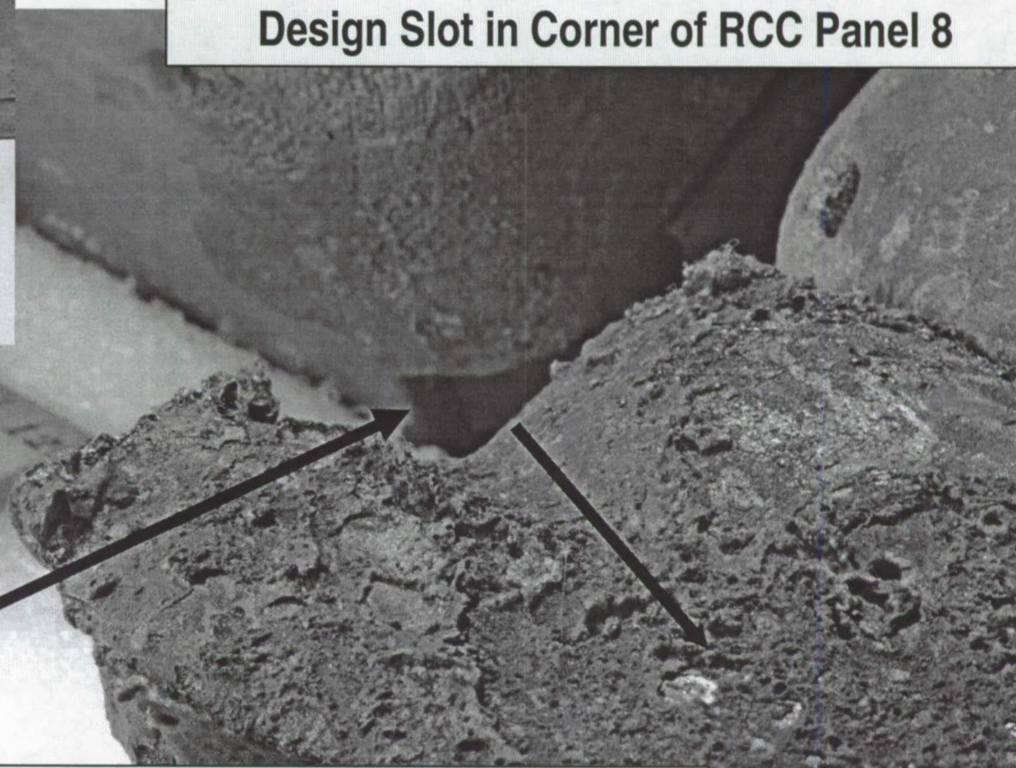


7025 internal side shows presence of deposits

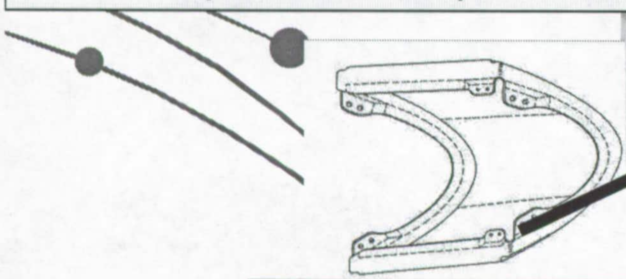
Slumping Source for Carrier Panel 9 Tile was Revealed



Slumping of C/P 9 Tile #1 Corresponds with Design Slot in Corner of RCC Panel 8



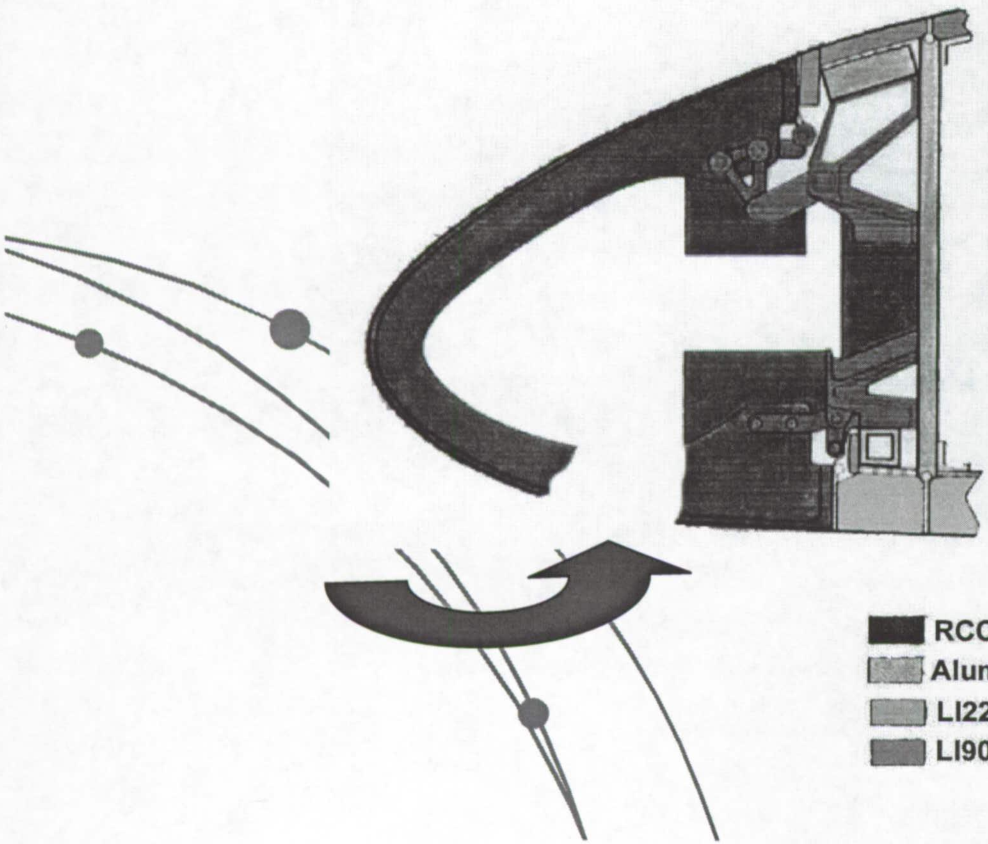
Slumping and erosion patterns suggest plasma flow across the carrier panel tile (from 8 toward 10)

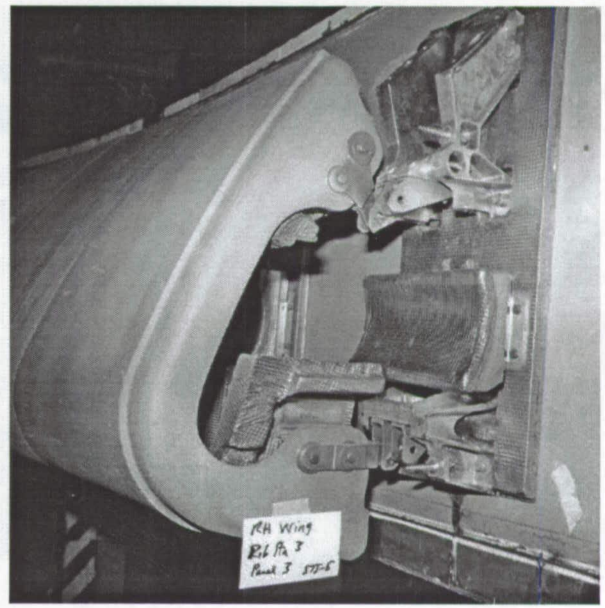


Evidence of Hot Gas Flow Exiting Design Slot Indicates Significant Breach Was Into Panel 8

Debris Indicates Highest Probability Initiation Site

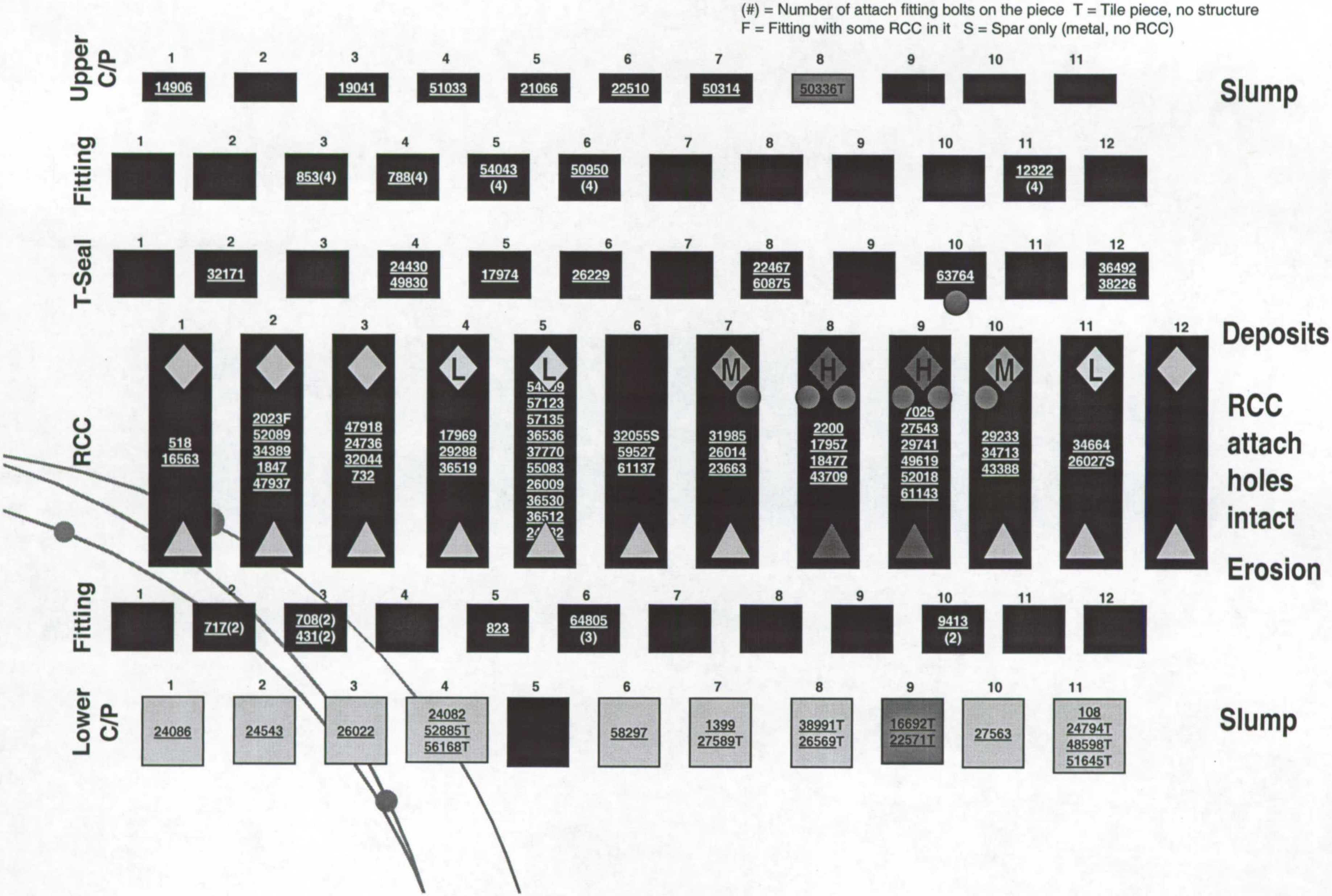
- Wing failure initiated in the panel 8 area
  - Most likely at the panel 8 area near 8-9 joint
  - Condition existed before or shortly after entry interface





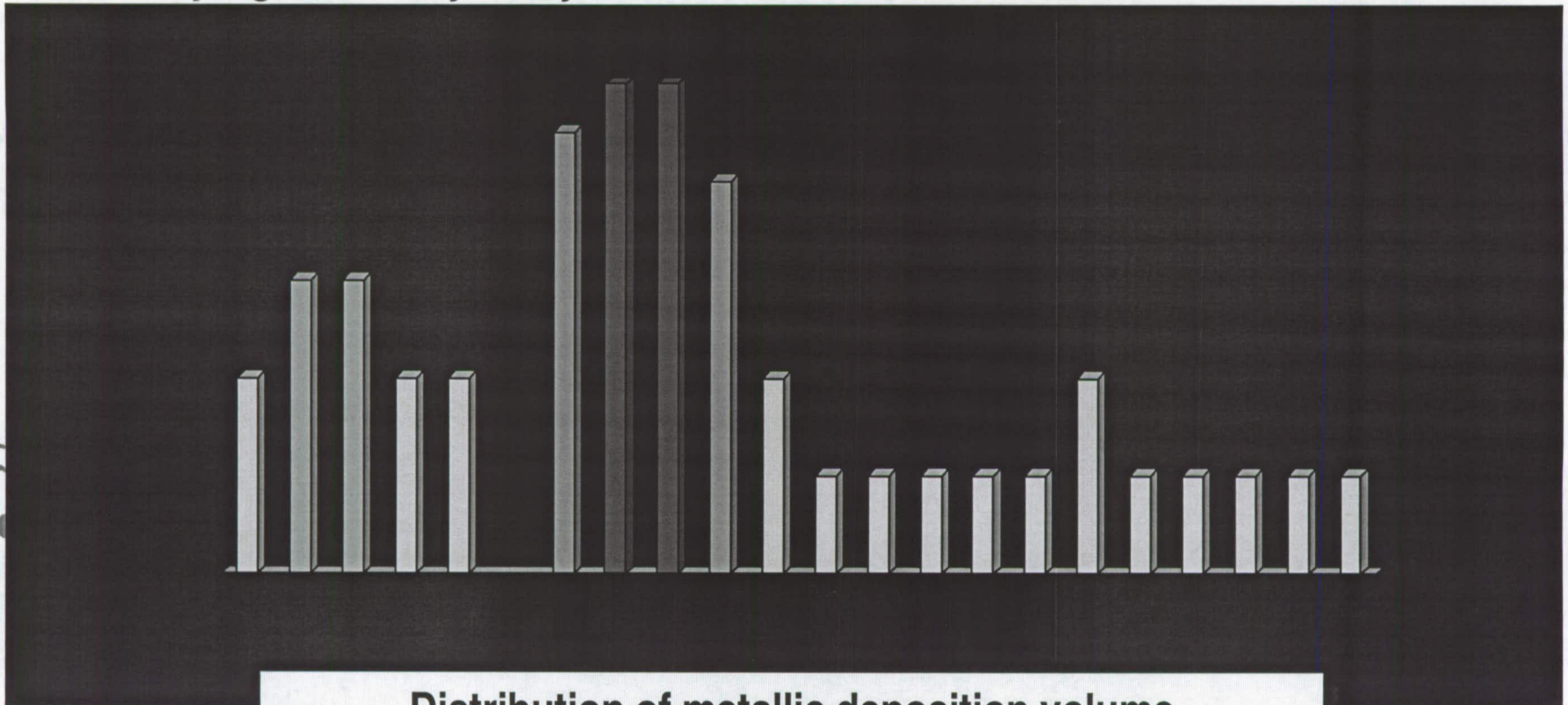
RCC
Aluminum
LI2200
LI900
Inconel-Dynaflex
Inconel 718
A-286 steel

Left Hand Wing Debris Points to RCC 8/9



Relative Metallic Deposition on L/H Wing Materials

Qualitative deposition assessment: from "Very Light" to "Very Heavy"

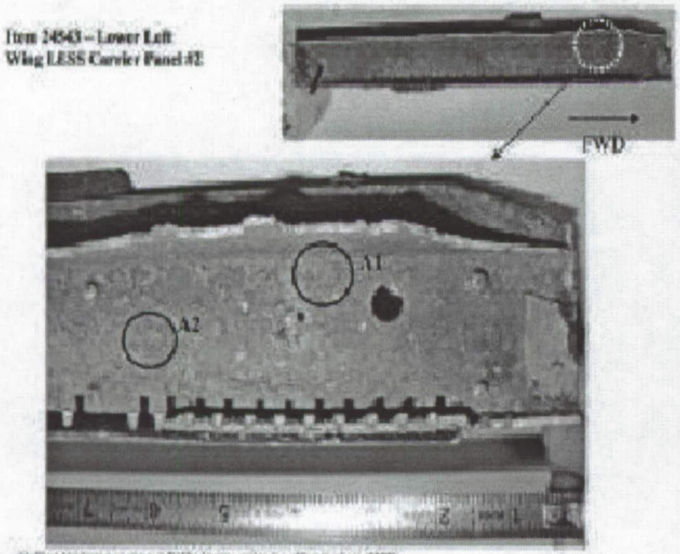


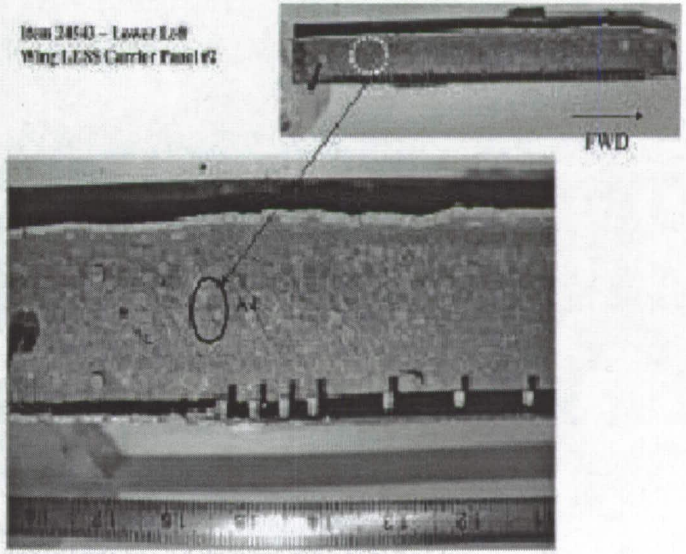
Distribution of metallic deposition <u>volume</u> was centered around panels 8 & 9

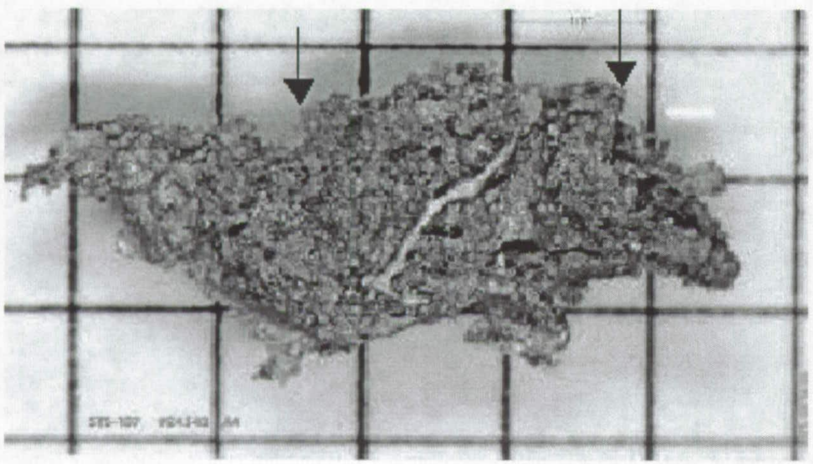
Analytical Tools

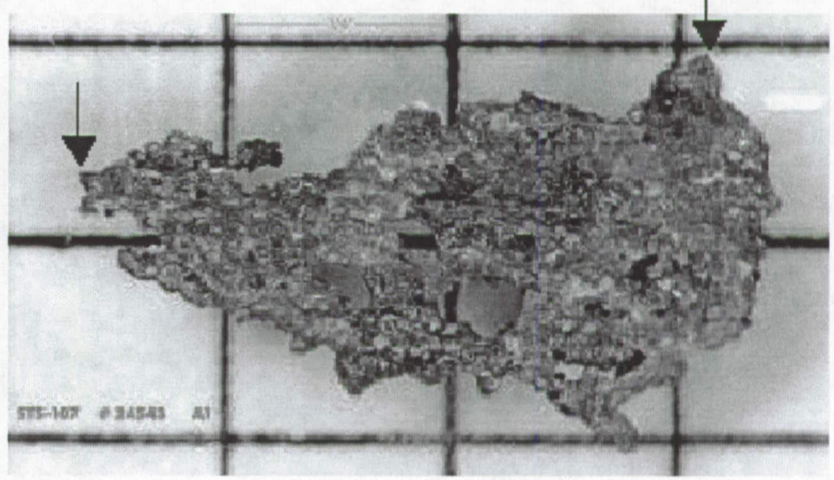
TOOL:	APPLICATION:
• Photography	Traceability, preservation
• SEM/EDS top and bottom of sample	Elements present, identify difference between
• X-ray Diffraction – XRD	Identify compounds of crystalline structure
• Electron Microprobe	Elemental ID and exact composition
• Fourier Transform Infra-Red – FTIR	Qualitative organic ID
• ESCA/XPS oxide; compound identification	Aid in tracking of oxidation states, such al
• Materiallography/ SEM layers	Layering and composition through deposit
• Inductively Coupled Argon Plasma – ICAP sample	Elements present, quantify bulk composition of
• Radiography	Subsurface roadmap, nondestructive

Lower Left Carrier Panel #2



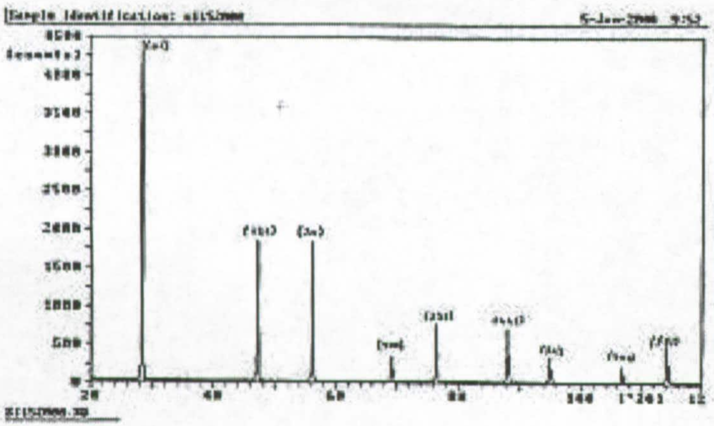






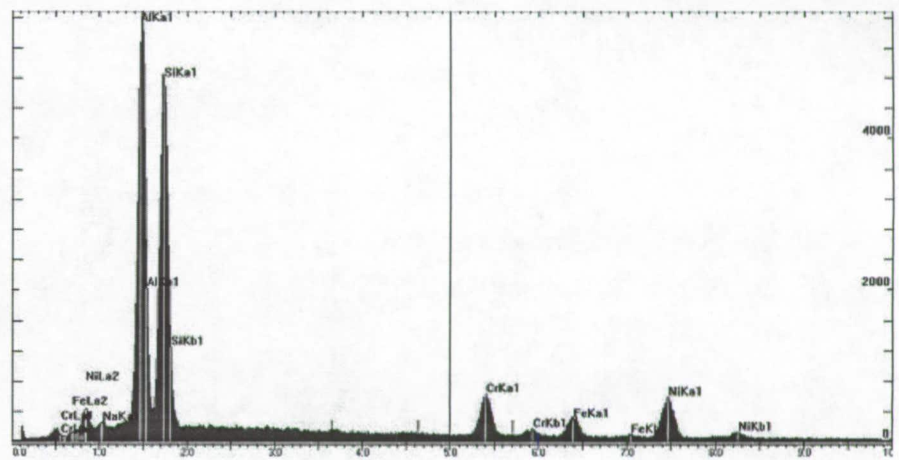
Typical EDS, XPS, and XRD results:

XRD



EDS

	Elements Detected (Approximate Weight %) via SEM/EDS									
	Na	Mg	Al	Si	Ca	Ti	Cr	Fe	Ni	Cu
A1 inner										-
Region 1	<1	-	33	38	-	-	8	5	15	-
Region 2	<1	-	32	37	-	-	8	5	18	-
Region 3	<1	-	32	37	-	-	7	5	19	-
Region 4	-	-	31	31	-	-	7	7	24	-
Region 5	-	-	29	29	-	-	8	7	26	-
Region 6	-	-	30	30	-	-	8	7	26	-
Region 7	-	-	31	34	-	-	7	6	22	-

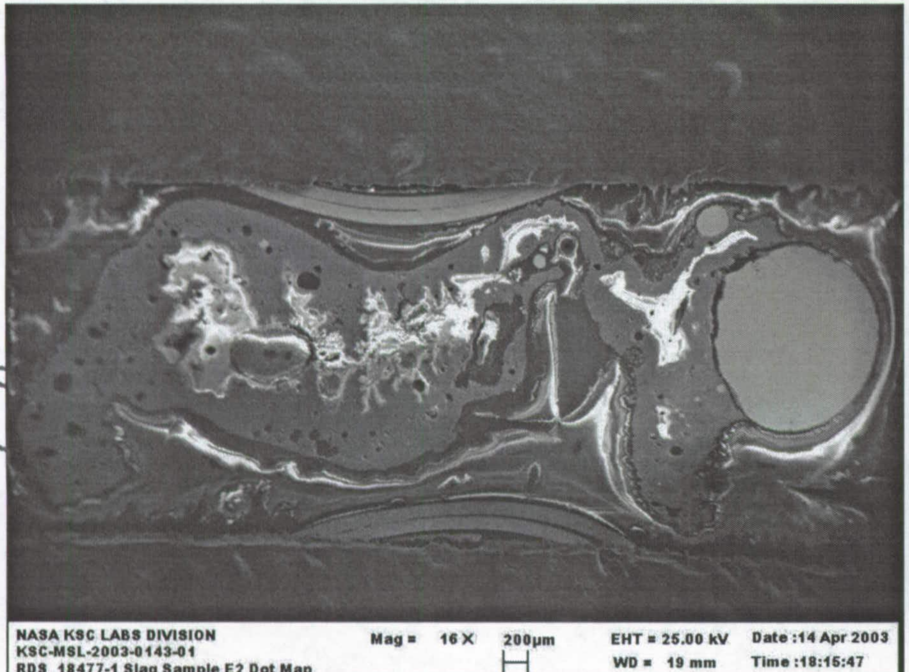


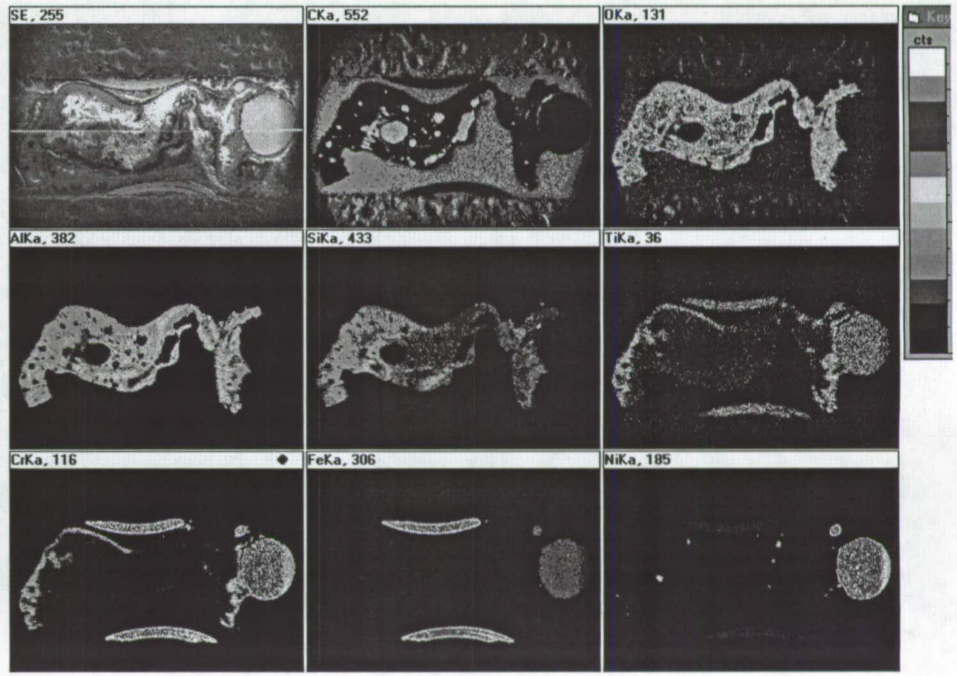
ESCA/XPS

Pressure: 1 X 10^{8} torr
Conditions: Magnesium X-rays at 15 KV and 12 mA

Element	Position, Binding Energy (eV)	Possible Compound(s)	Mass Concentration (weight %)
O 1s	532.050		58.29
Al 2p	75.050	Al_2O_3, minor Aluminum silicate	22.29
Fe 2p	710.050	FeO and Fe_2O_3	2.47
Cr 2p	575.750	CrO_2	7.61
Cu 2p	932.850	Cu metal	2.20
Si 2p	102.550	Al silicate	5.23
N 1s	399.150		1.91

SEM/EDS Dot Mapping

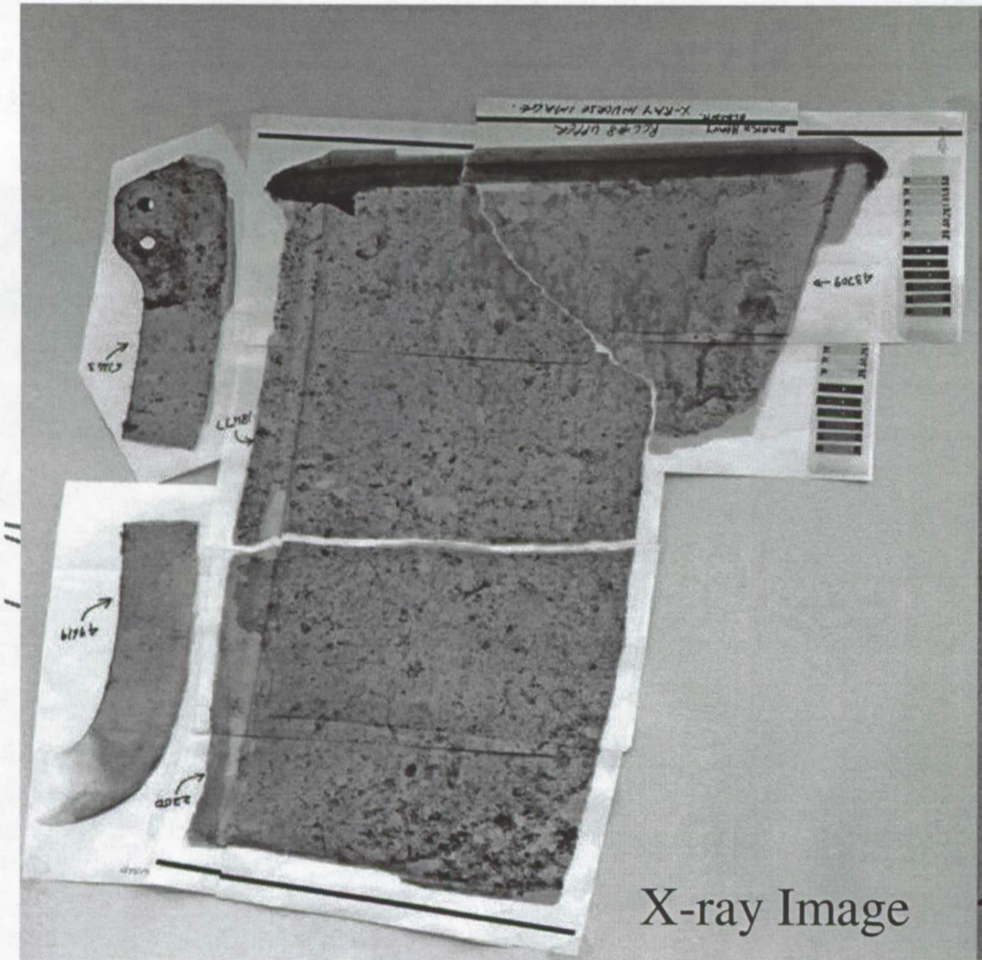


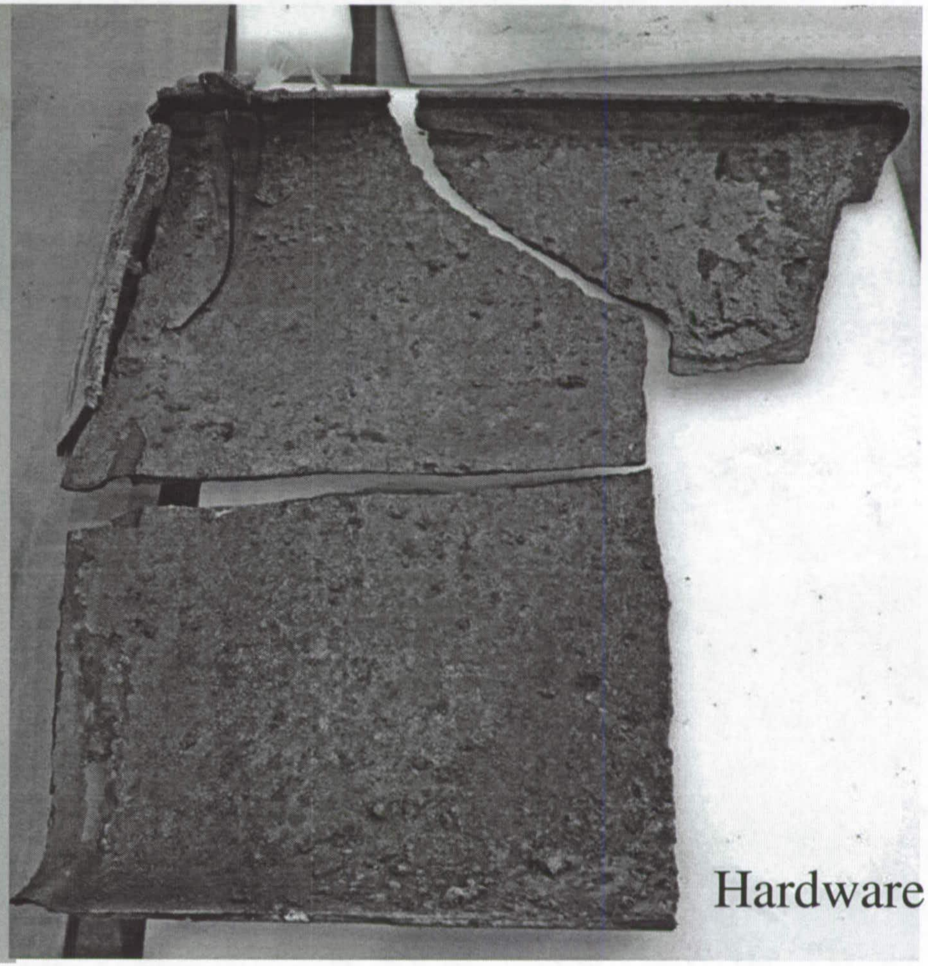


Required Quantitative Interpretation

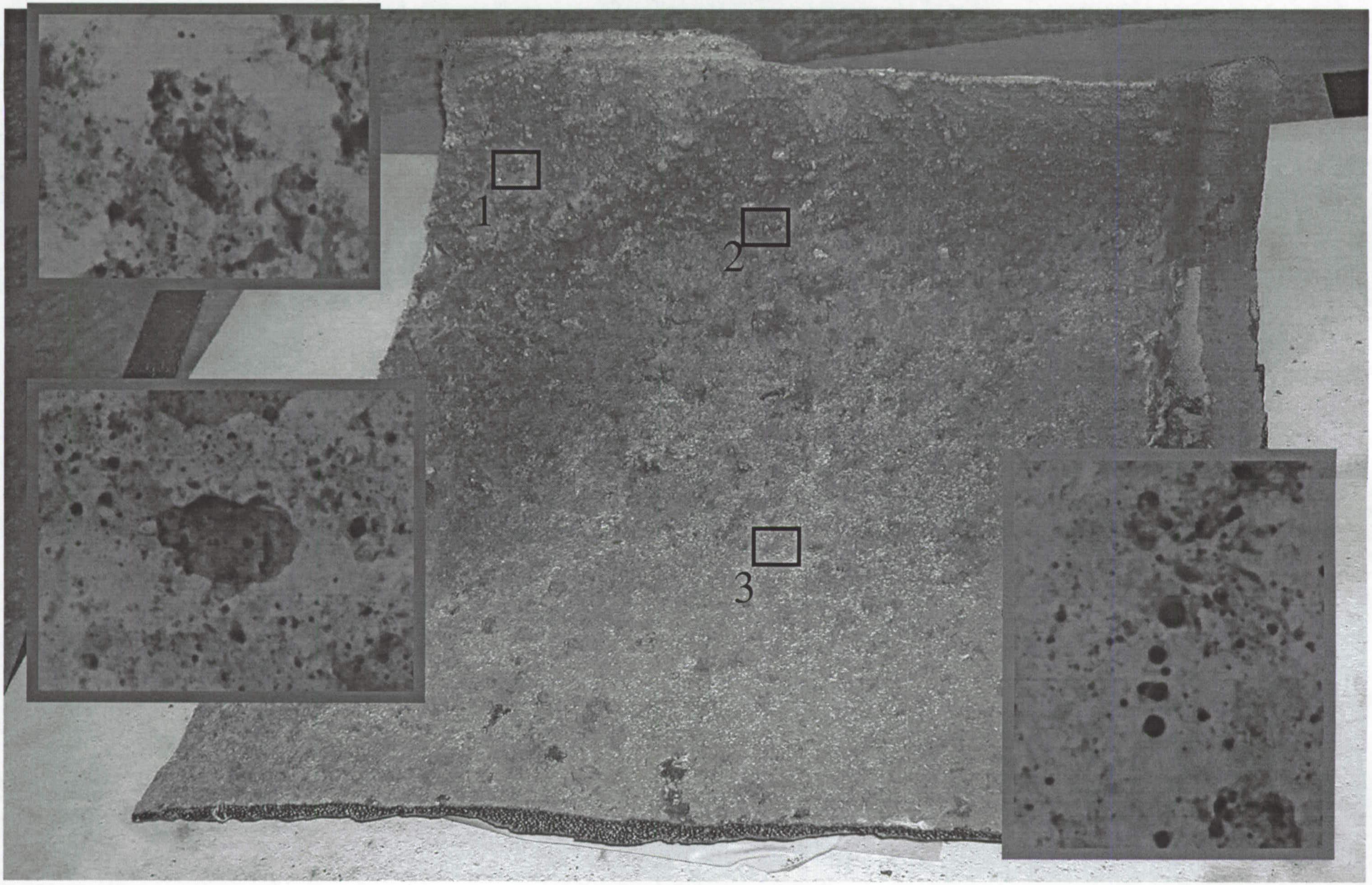
- **Specific alloy identification in deposits:**
  - A286 or IN601, IN718, IN625 can be distinguished based on (Ni/Fe) ratio and evidence and amounts of Mo, Nb, Co and Ti.
  - 2024 can be identified by presence of metallic Al + Cu, Al_2O_3 + Cu.
- **Identify Cerachrome in deposit:**
  - Cerachrome is approximately 43%$Al_2O_3$53%$SiO_2$3%Cr_2O_3.
  - It can be identified from a combination of back-scattered imaging, color, x-ray diffraction and presence and quantification of Al, Si, O, & Cr.
- **Identify SiO_2 source:**
  - SiO2 from tile will not have with other elements as in cerachrome. It could still pick up a coating of alumina then morphological features will be used to distinguish.

Radiography WLE LH Panel 8

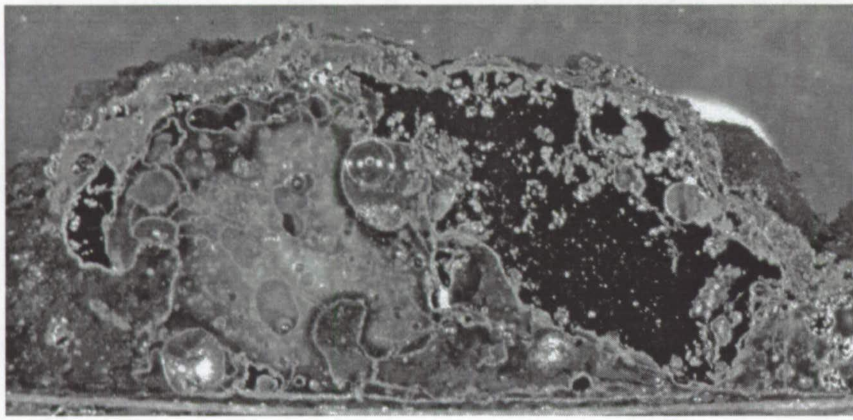




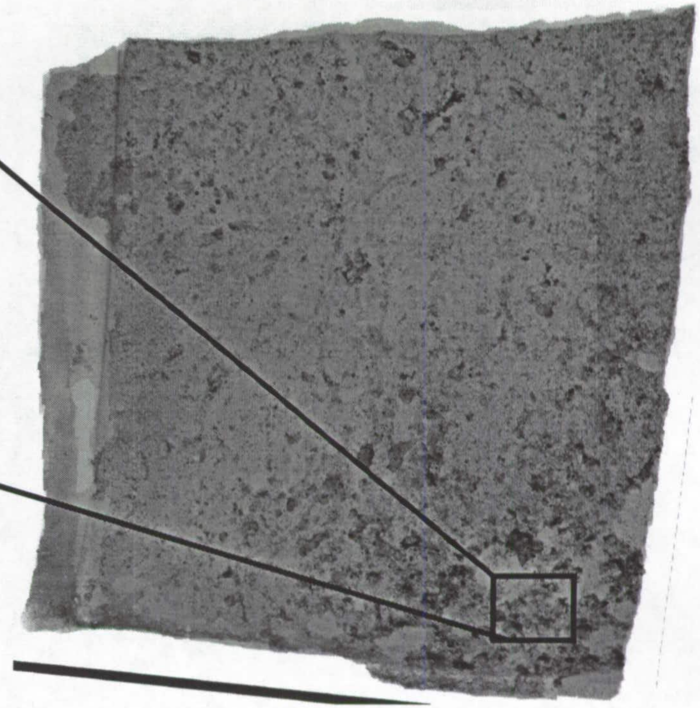
LH RCC 8 Upper Apex



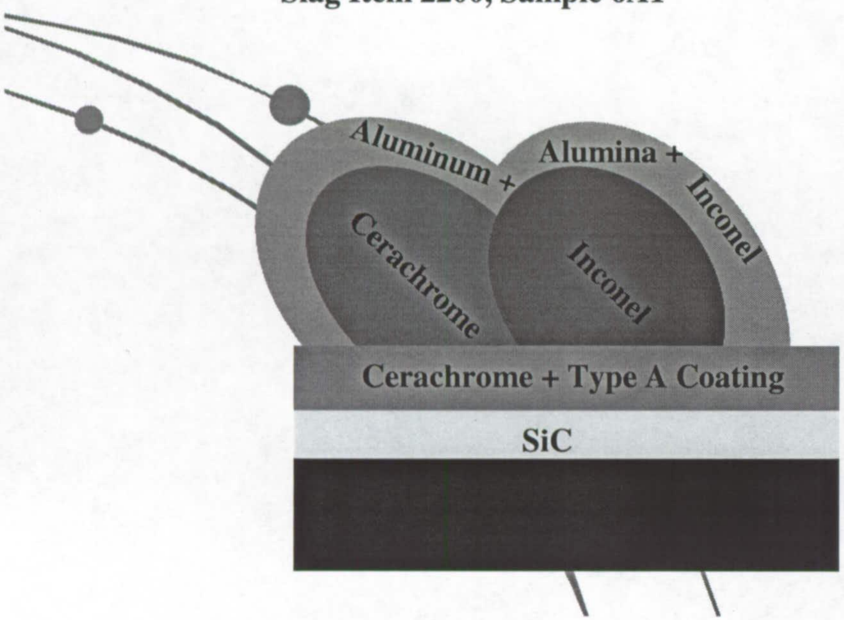
LH RCC #8 - Slag Feature 2 Thick Globules



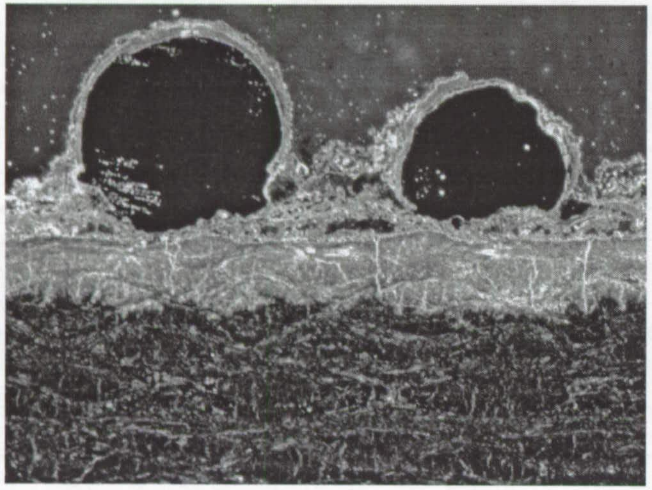
Slag Item 2200, Sample 6A1



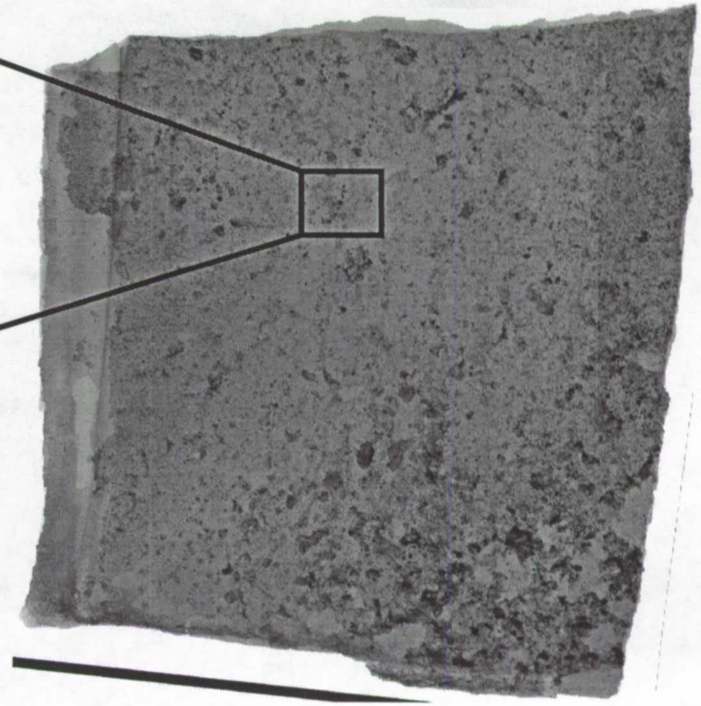
Radiograph of Item 2200



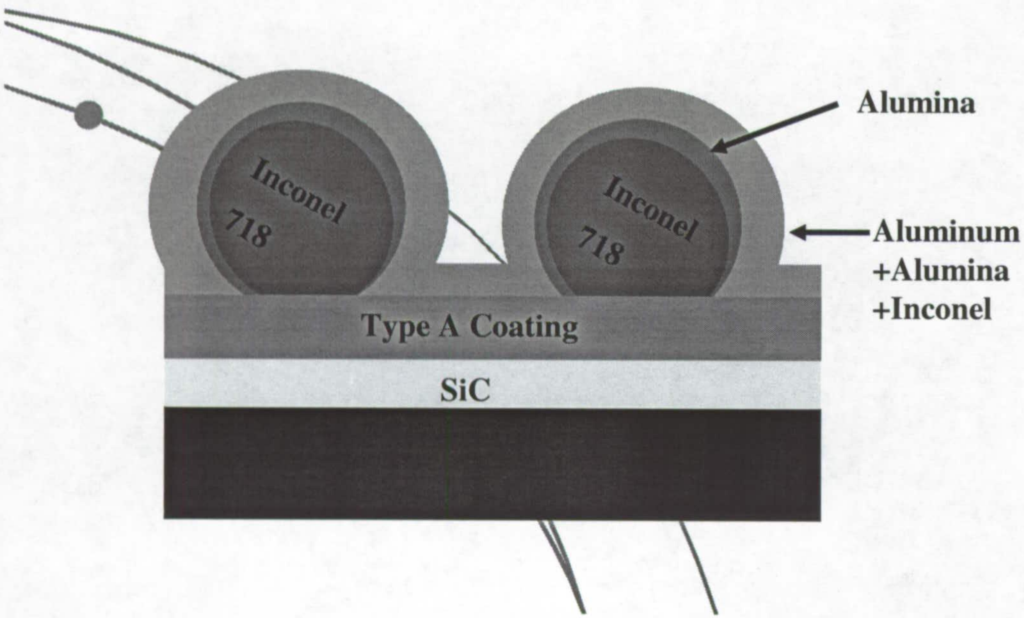
LH RCC #8 - Slag Feature 3 Spheroids



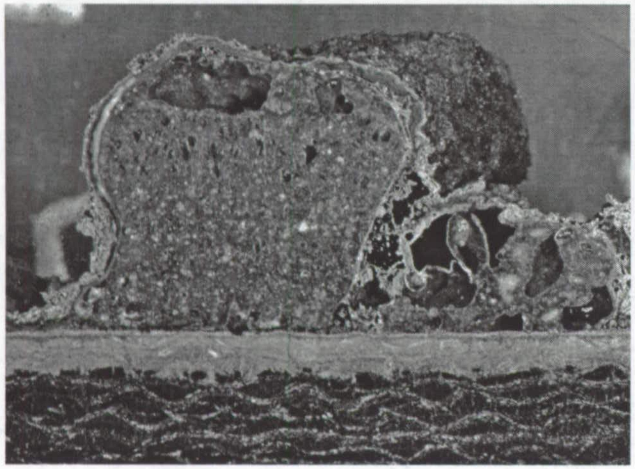
Slag Item 2200, Sample 6C1



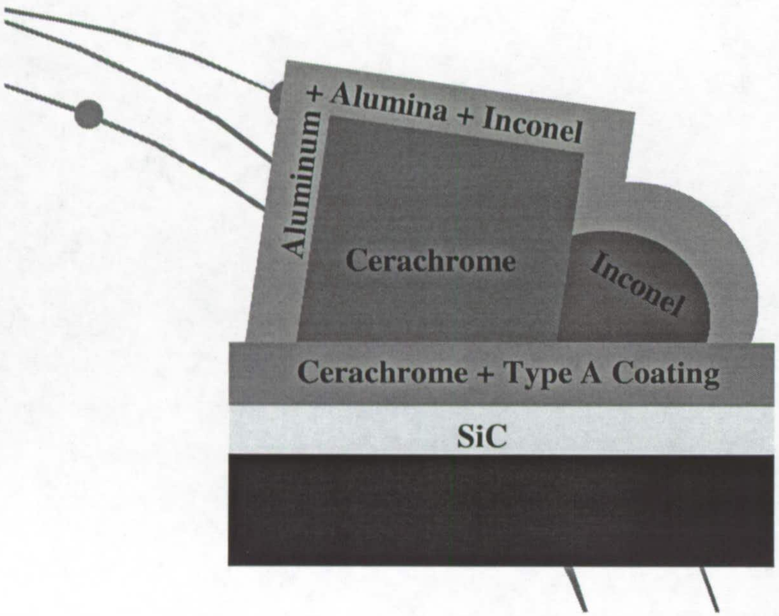
Radiograph of Slag Item 2200

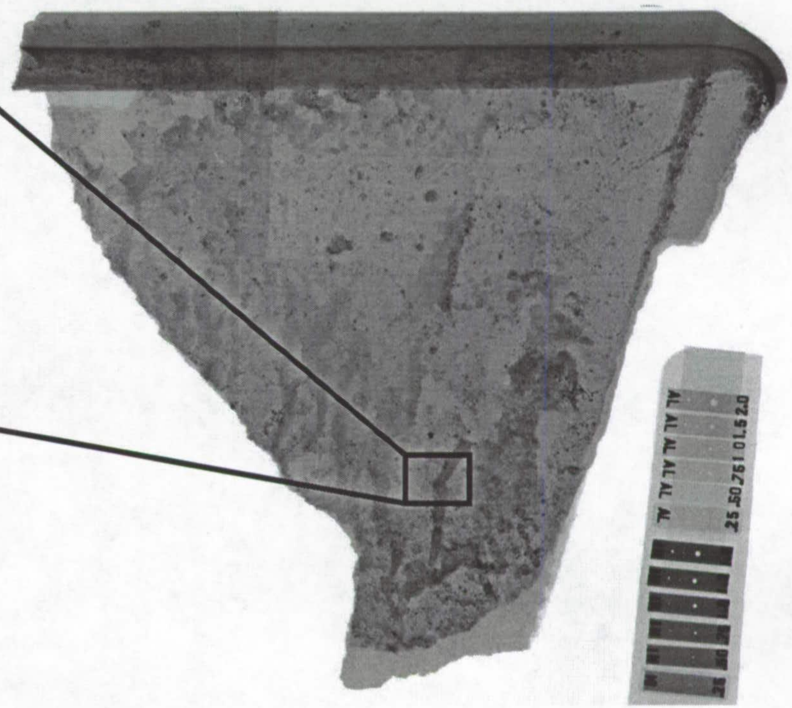


LH RCC #8 - Slag Feature 1
Tubular Shaped



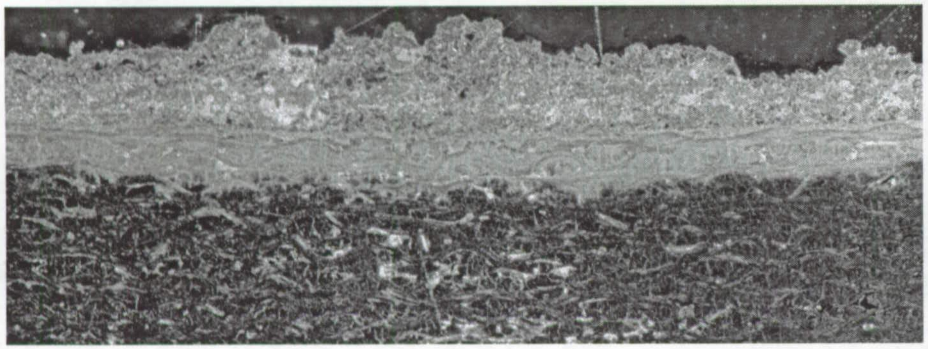
Slag Item 43709, Sample 2A1



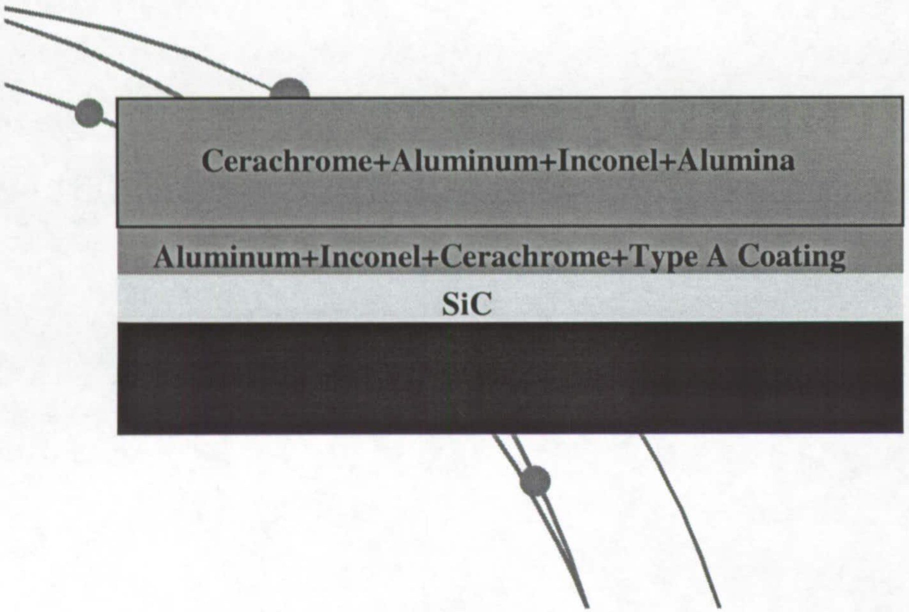


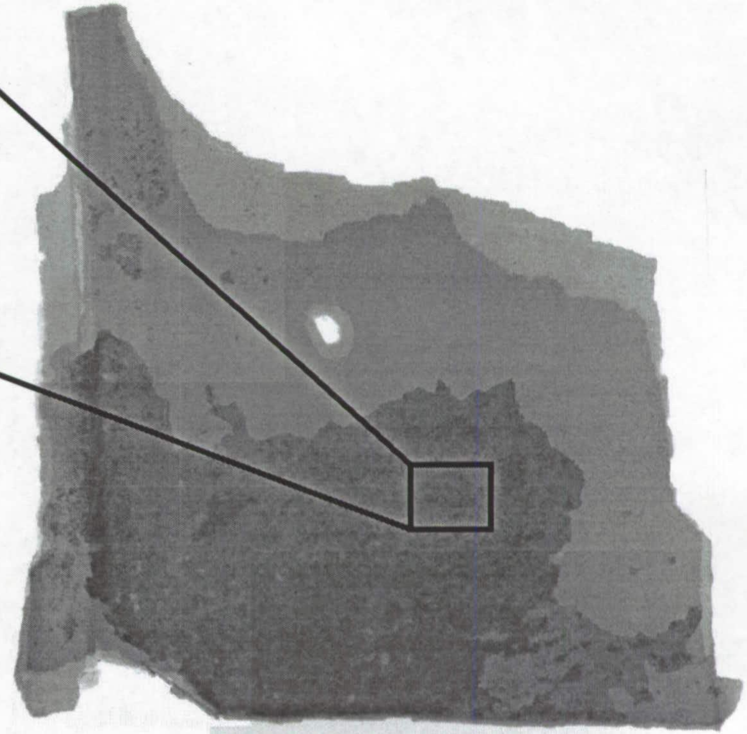
Radiograph of Item 43709

RH RCC #8 - Slag Feature 4
Uniform Deposit



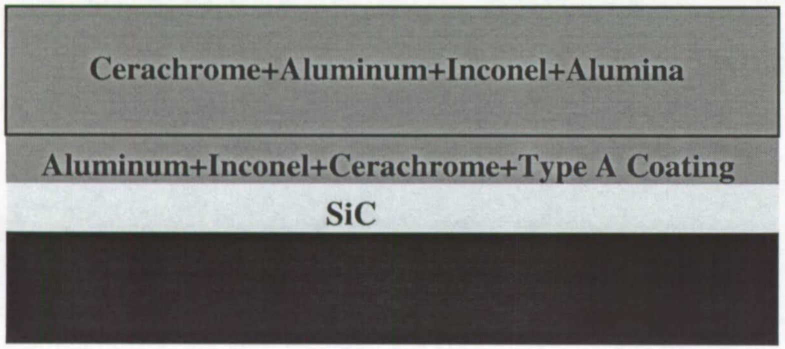
Slag Item 16523, Sample 4A1



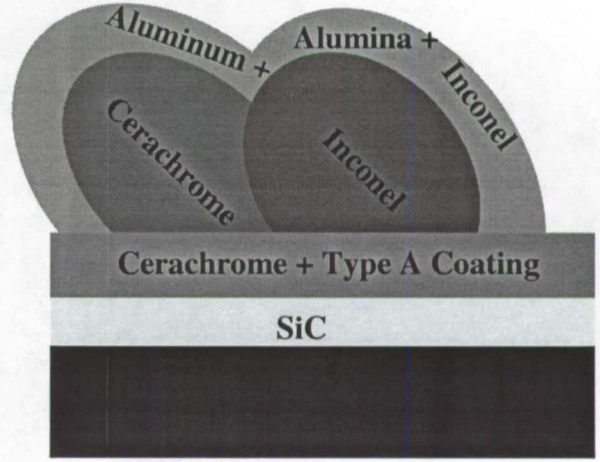


Radiograph of Item 16523

Deposit types via Micro-Probe

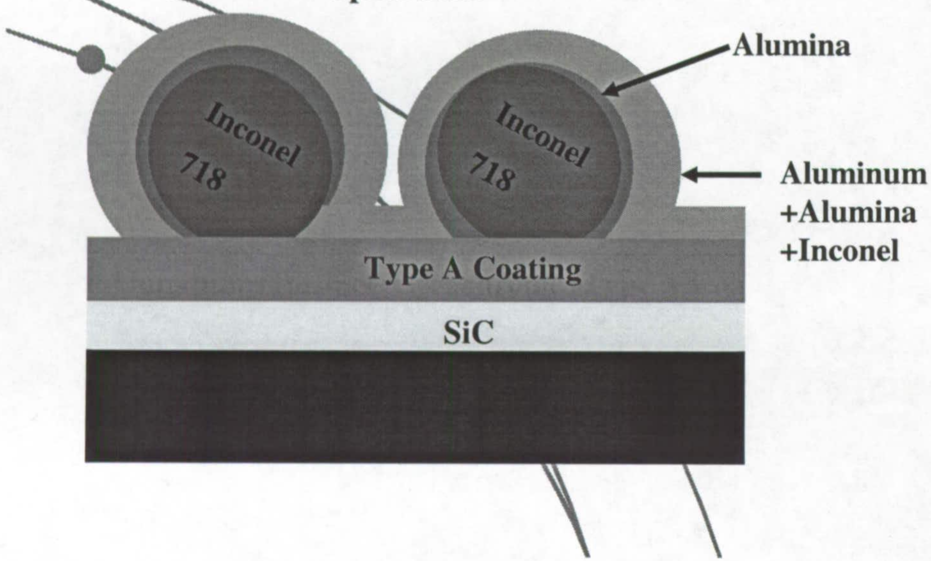


Typical

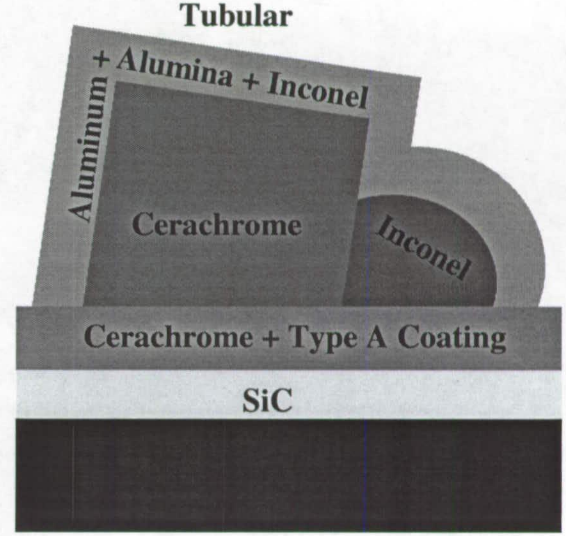


Globular

Spheroidal



Tubular



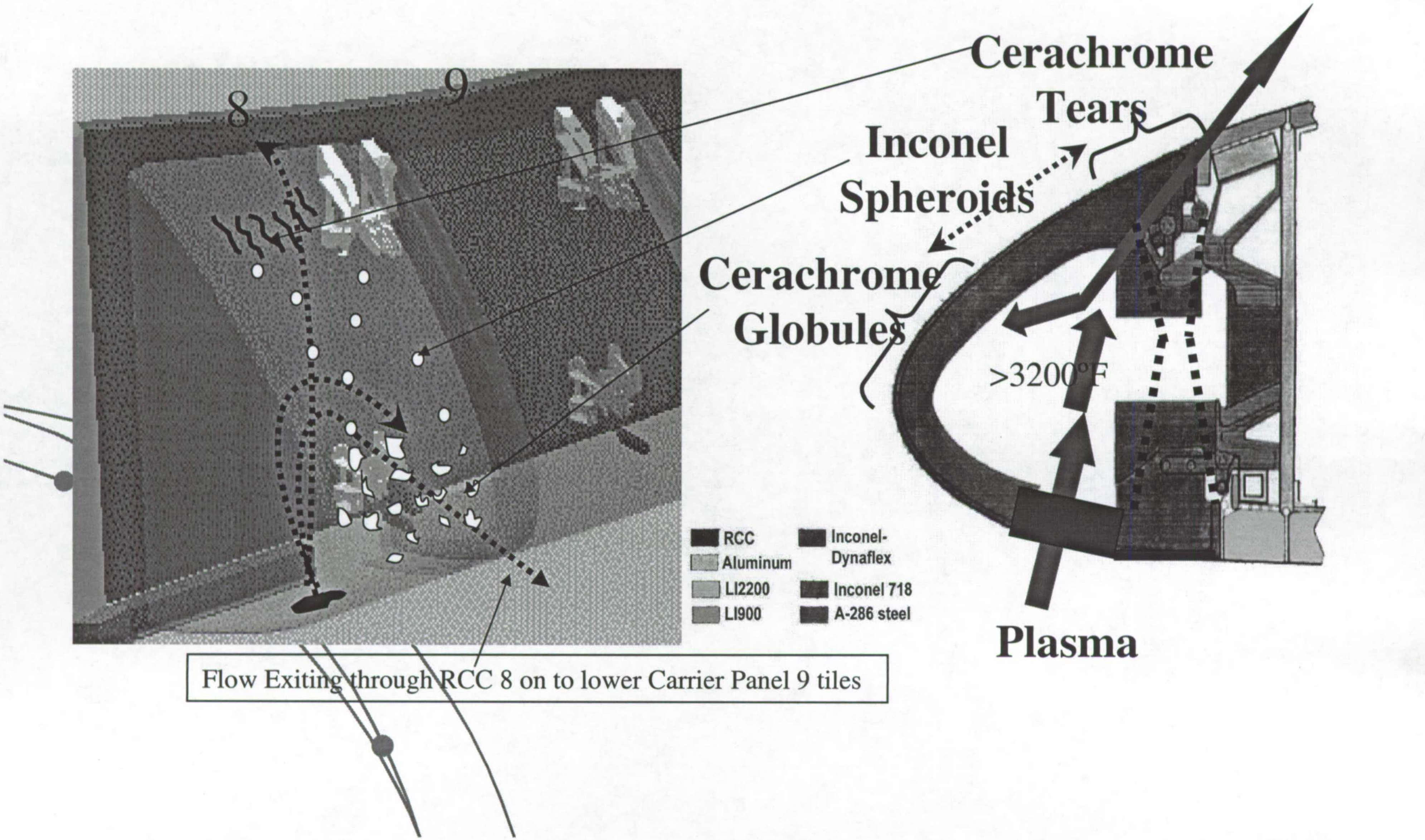
Significant Findings - Sampling LH RCC Panel 8

- Large amounts of melted ceramic cerachrome insulator
  - **High temperature >3200ºF**
- No indication of stainless steel spar fittings (A286) in deposit
  - **Breach location away from spar fittings**
- Cerachrome + Inconel in first deposited layers
  - **Melting of spanner/foil/fittings + Insulator**
- Aluminum deposition secondary event

Deposit layering suggests plasma impingement location

Deposit distribution & shape suggests plasma flow direction and deposition duration

Proposed Breach Location & Plasma Flow Based On Slag Results



Flow Exiting through RCC 8 on to lower Carrier Panel 9 tiles

Failure Sequence

•**Cerachrome insulation blankets** covered with Inconel 601 foil melt **and vaporize**

•**Wing carrier panel tile immediately aft of the breach slump**

•**RCC adjacent to, and downstream of, breach erode**

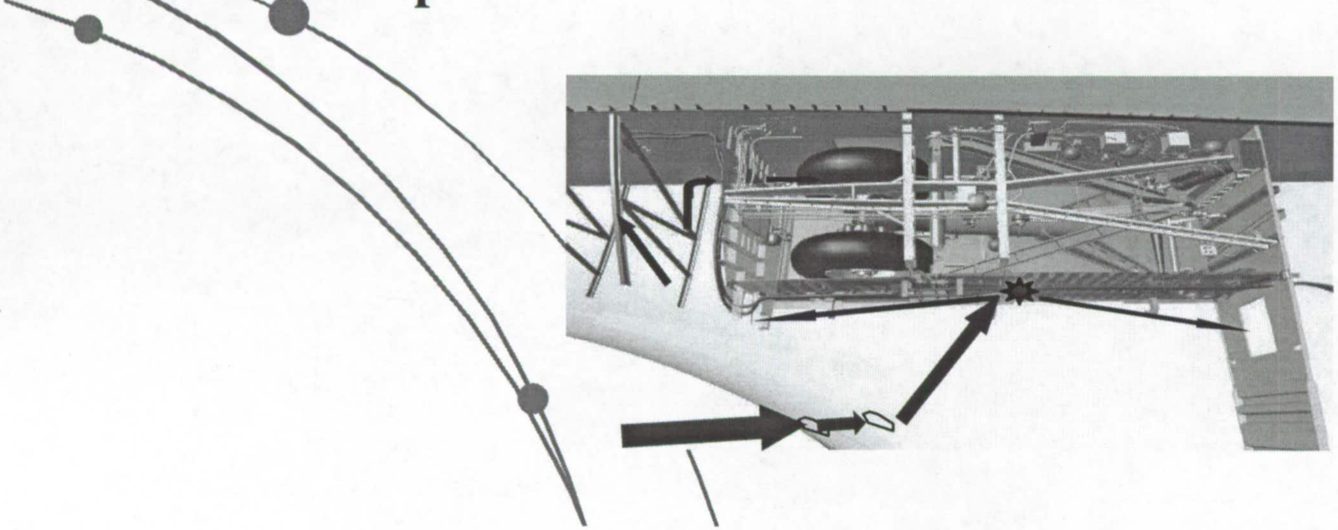
•**Inconel 718 and A286 leading edge attach hardware melt and/or weaken**

•**Instrumentation and wire bundles damaged**

•**Aluminum wing leading edge spar penetrated**

•**Wing internal structure degraded by plasma flow**

•**Wing structural failure leads to loss of vehicle control and break-up**



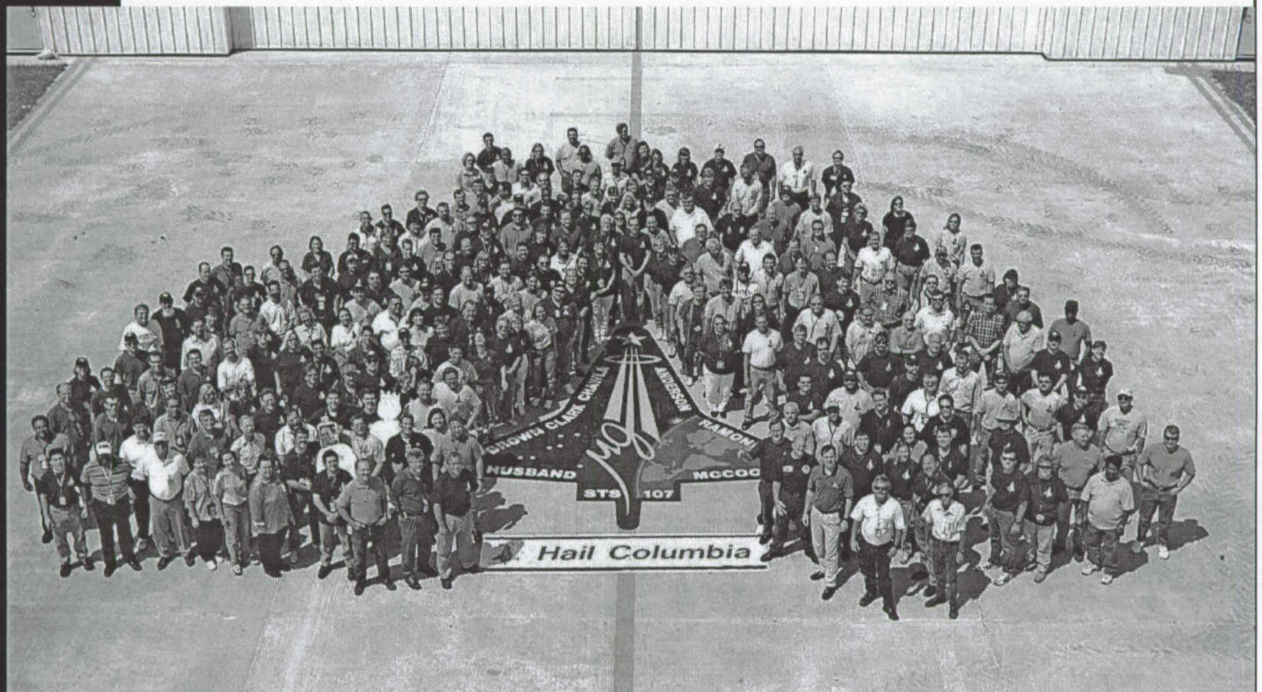
Vehicle Assembly Building Today

The M&P Team gratefully acknowledges the talents and contributions of the following individuals:

NASA-GRC
- Herb Garlick
- Leslie Greenbauer-Seng
- David Hull
- Nathan Jacobson
- Elizibeth Opila
- James Smialek

NASA-JSC
- Jay Bennett
- Glenn Ecord
- John Figert
- Julie Henkener
- Julie Kramer-White

NASA-KSC
- Larry Batterson
- Virginia Cummings
- Dionne Jackson
- Thad Johnson
- Hae Soo Kim
- Sandra Loucks
- Peter Marciniak
- Wayne Marshall
- Orlando Melendez
- Scott H. Murray
- Jaime Palou
- Donald Parker
- Victoria Salazar
- Eric Thaxton
- Stan Young
- M. Clara Zapata



NASA-LaRC
- Robert BErry
- Stephen Smith
- William Winfree

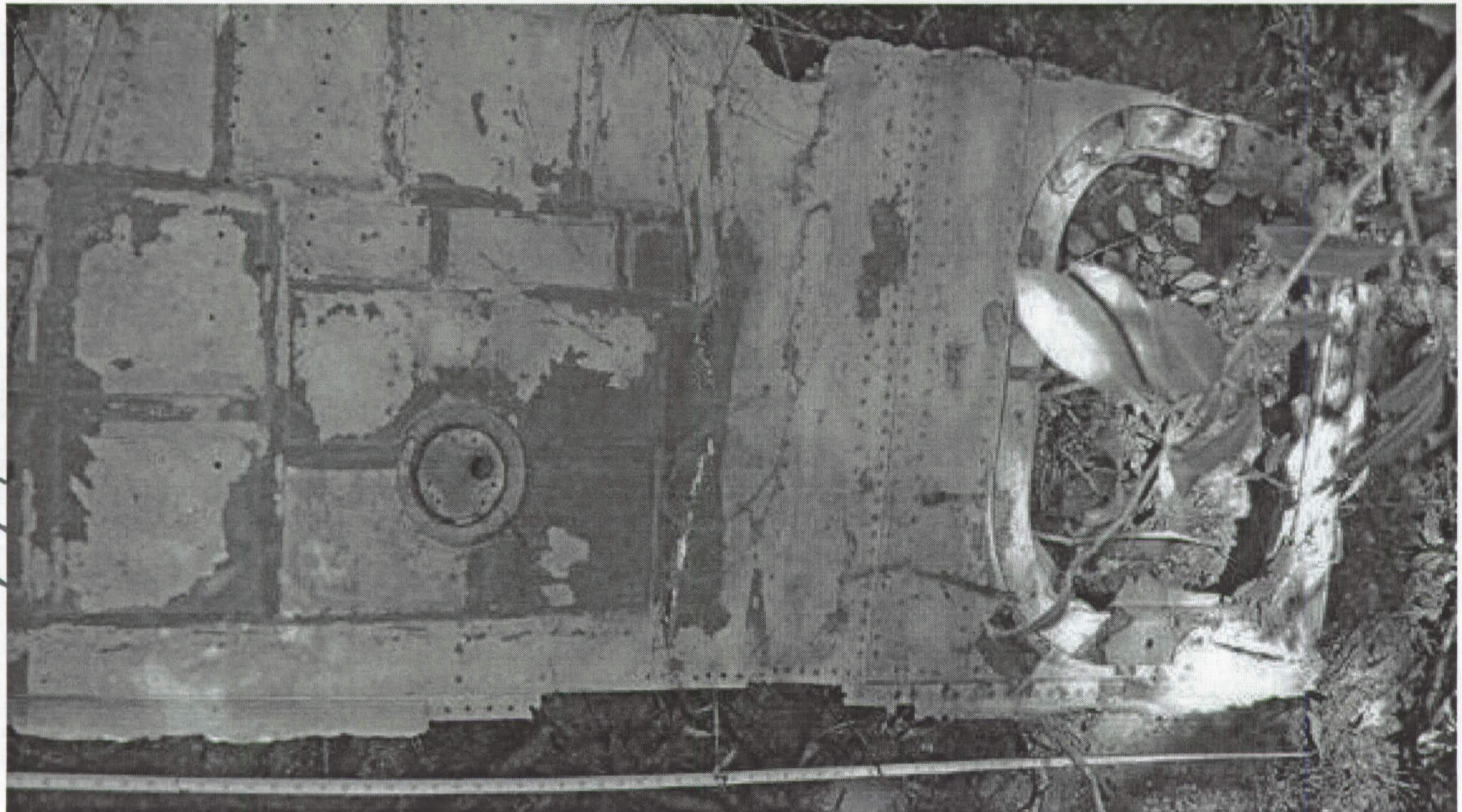
NASA-MSFC
- James Coston
- Greg Steele

Boeing
- Rodger Capps
- Tab Crooks
- Jeff Hausken
- Stephanie Hopper
- Mark Hudson
- Dave Lubas
- Robert Perez
- Keith Pope
- Janet Ruberto
- Keith Pope
- Jim Stewart

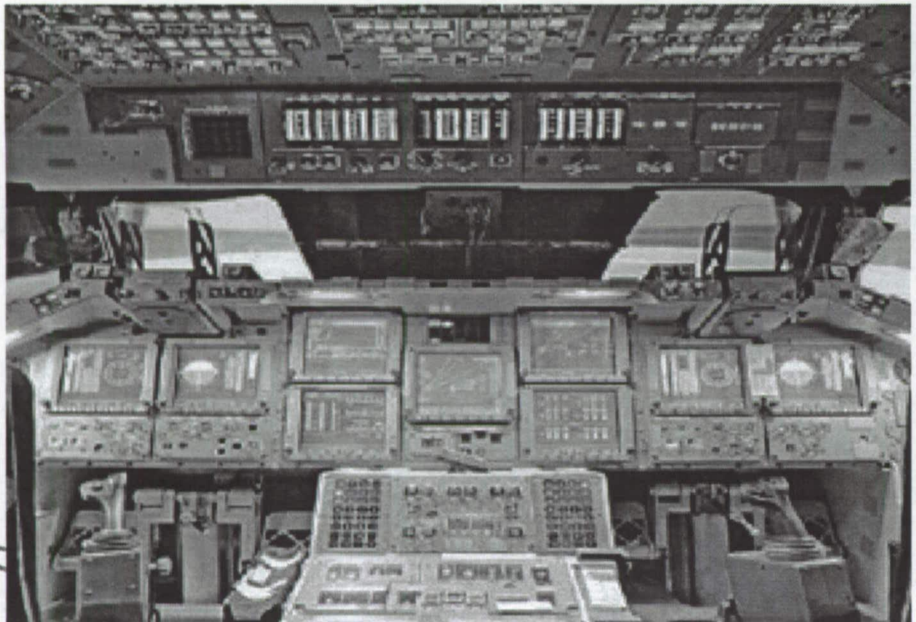
USA
- Cathy Clayton
- Stanley Schultz
- Bryan Tucker

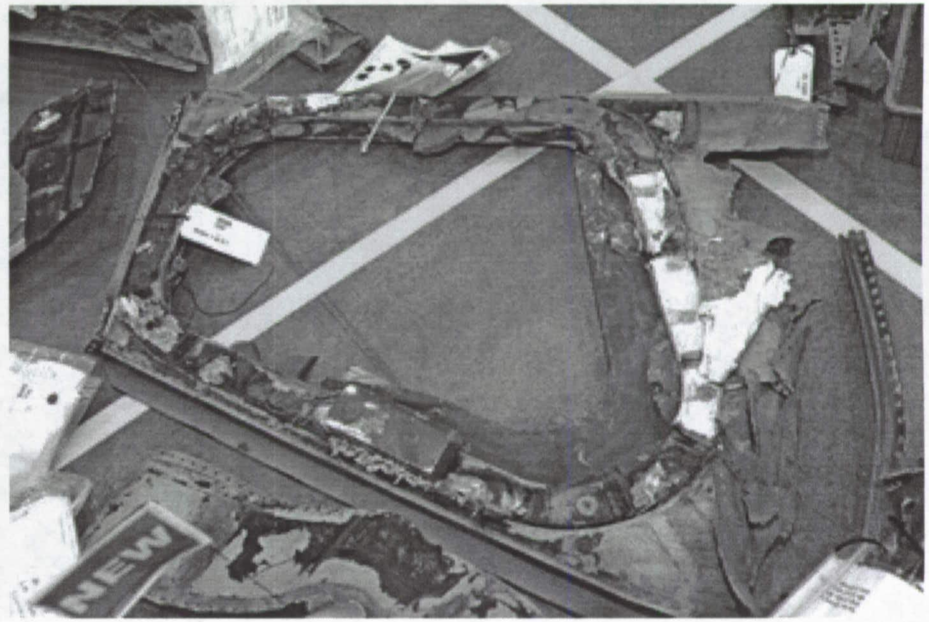
CAIB
- Dr. Gregory T. A. Kovacs
- G. Mark Tanner

Found One Year After Loss of Columbia



Cockpit Windows



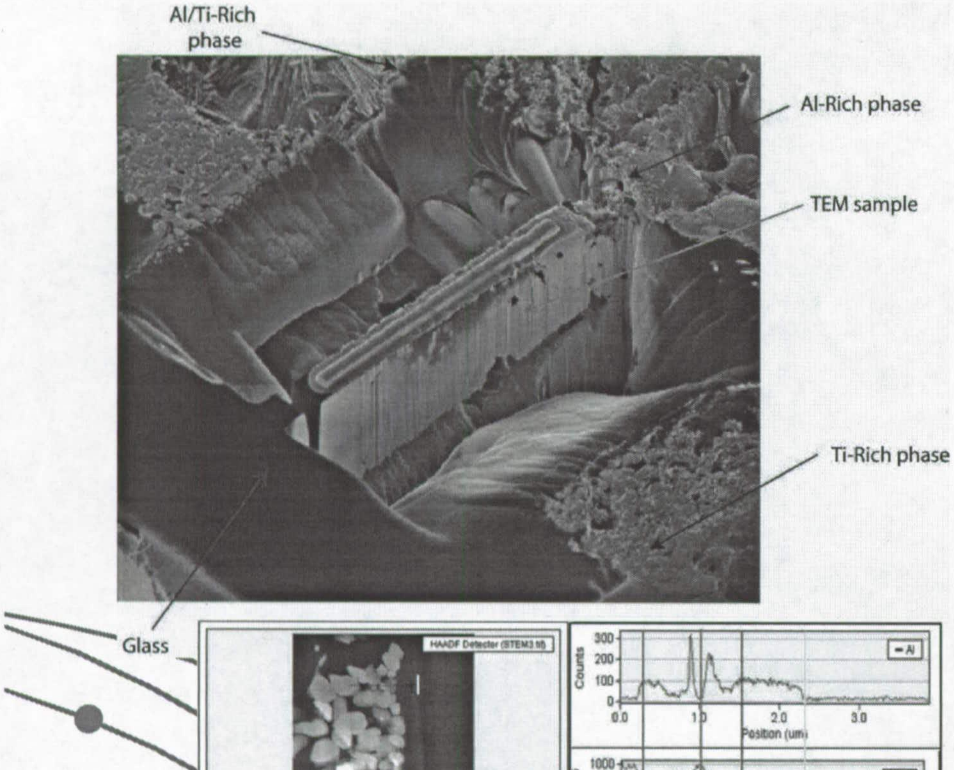


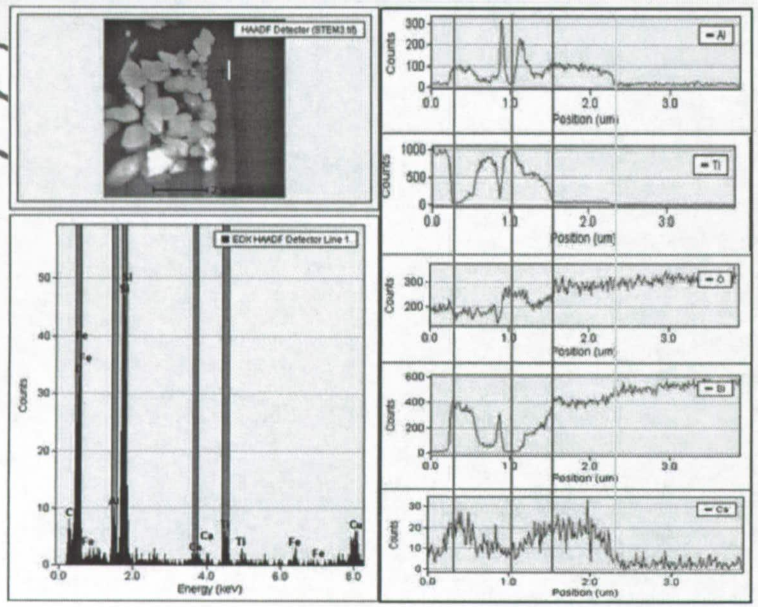
•Each consists of three individual panes. The innermost Pressure pane is constructed of tempered aluminosilicate glass to withstand the crew compartment pressure.

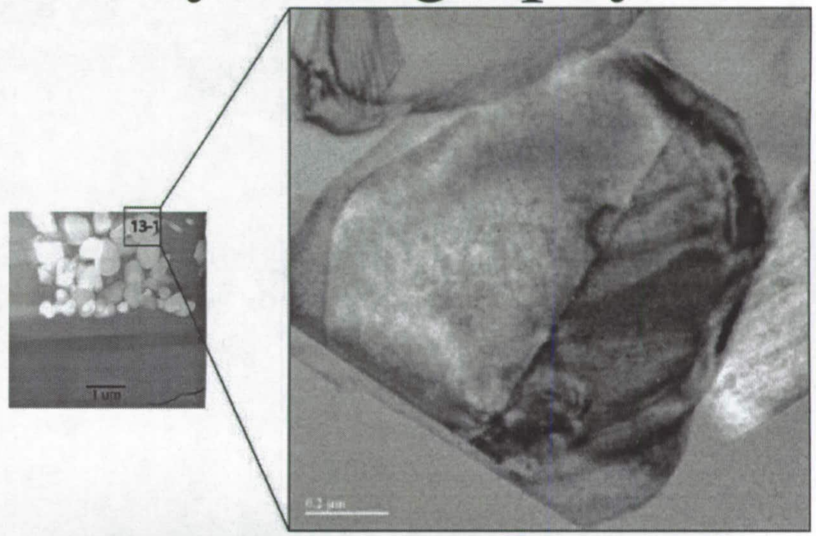
•The exterior of this pane, called a Thermal pane, is coated with a red reflector coating to reflect the infrared (heat portion) rays while transmitting the visible spectrum.

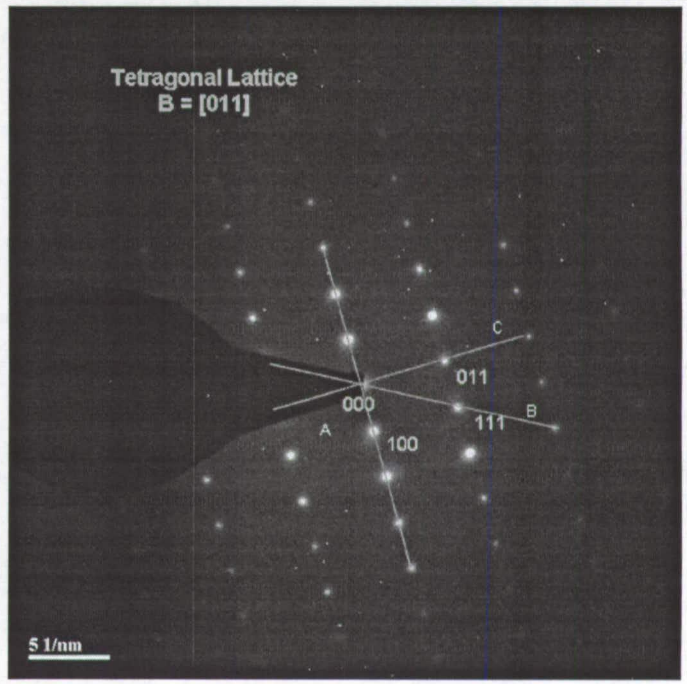
•The center redundant pane is constructed of low-expansion, fused silica glass because of its high optical quality and excellent thermal shock resistance.

Window Samples:
Focused Ion Beam/TEM/Crystallography

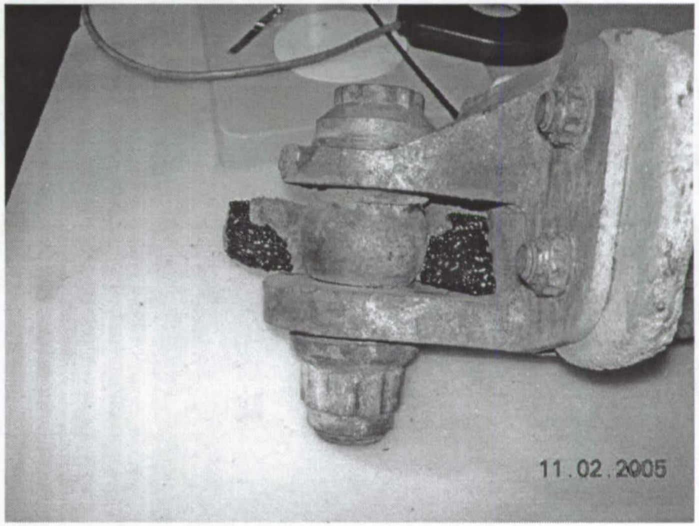


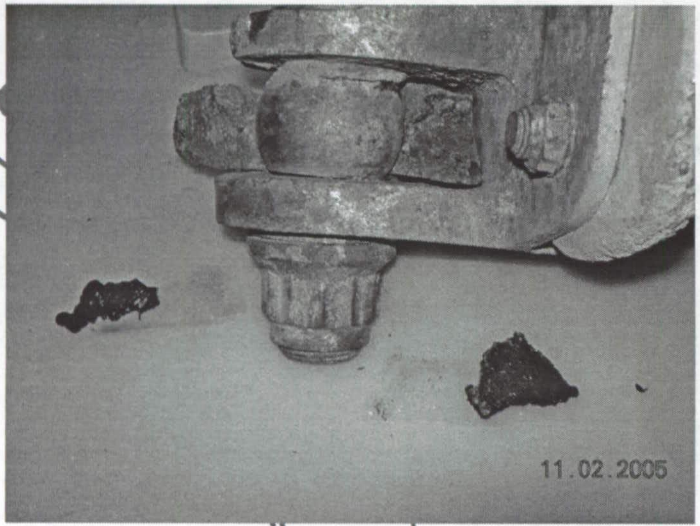






Z-Link Fracture with Replicas

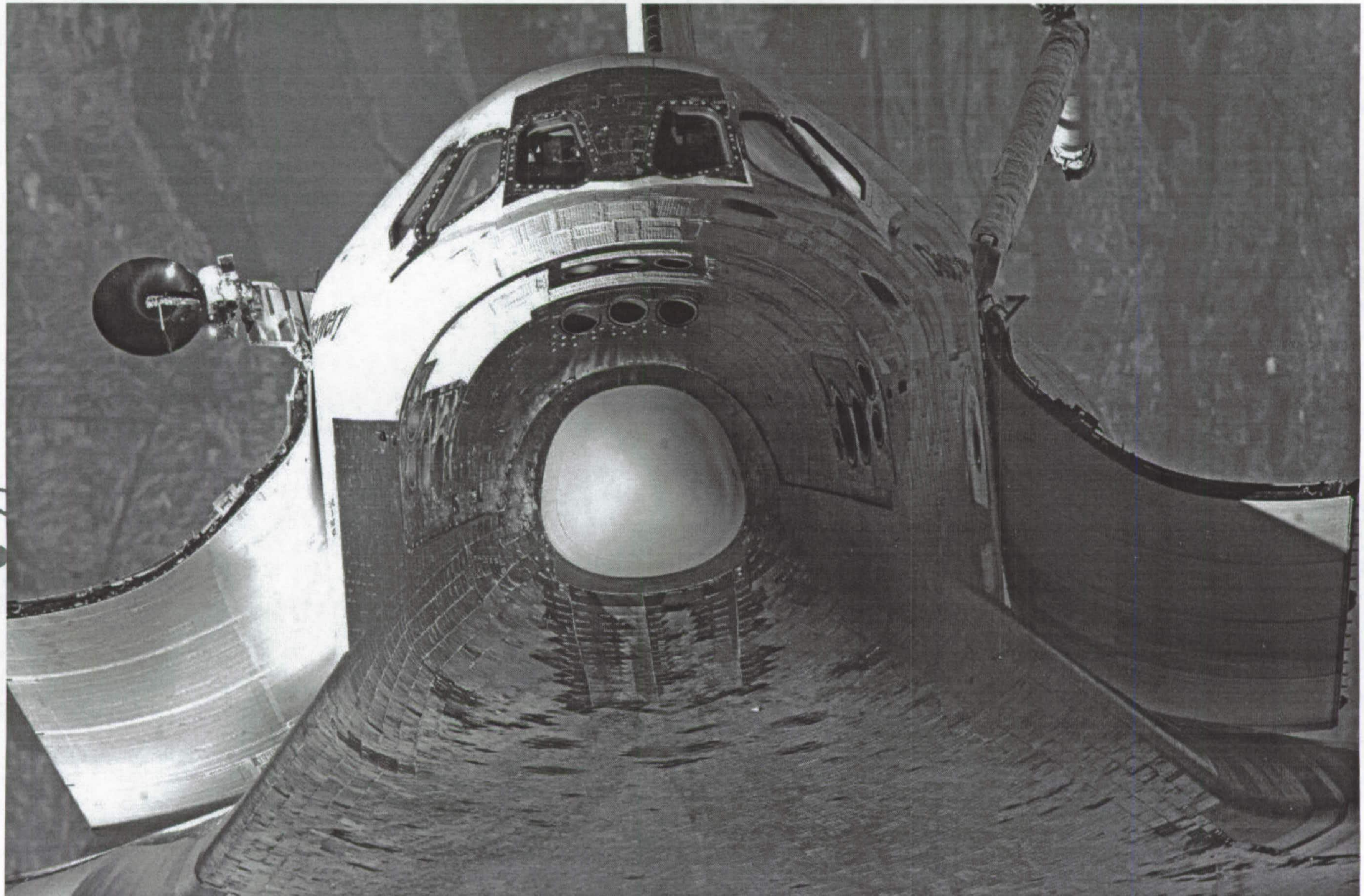




Return To Flight Enhancements

- Bolt catchers redesigned (one piece instead of two)- Used when SRB's separate from ET)
- Wing sensors- 22 per wing to record temperatures and impacts
- Augmented cameras and tracking- On the underside of the Orbiter, ground based, and airborne
- Bipod ramp heaters- replaces foam insulation in areas where the ET attaches to the Orbiter
- LOX feedline bellows- The bellows move as they transport -297 degree fuel from the ET to the Orbiter; they can't be insulated. Heaters will minimize ice formation.

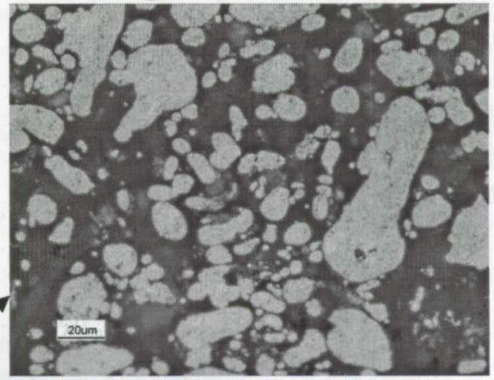
Return to Flight



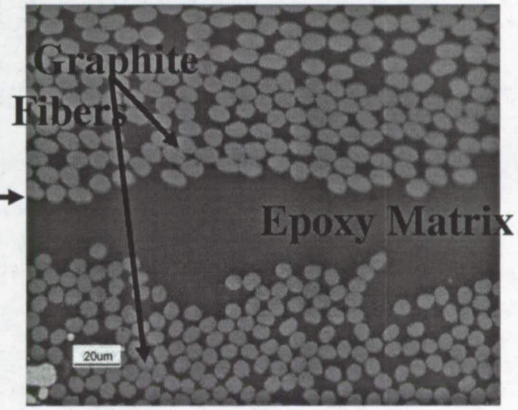
Columbia Debris Analysis
Lehigh University
Department of Materials Science and Engineering

Payload Bay Door

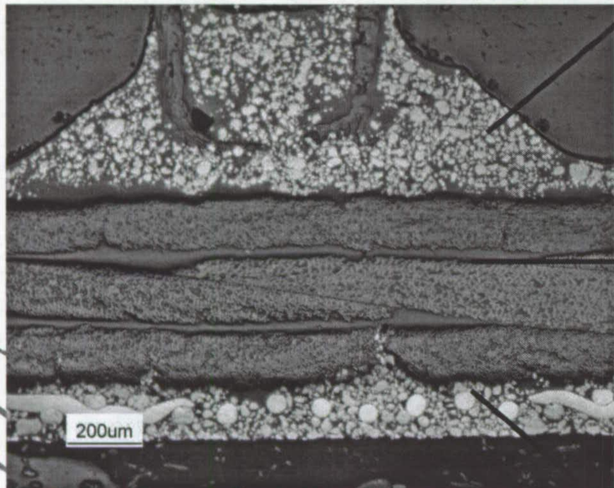
David Fischer, Lehigh University



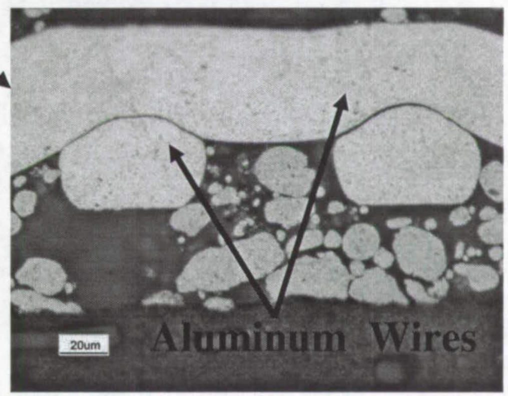
Honeycomb support composed of various sized particles



Graphite fibers oriented in various directions within epoxy matrix



LOM image shows three distinctive inner layers of debris



Aluminum wires form metal mesh

Columbia Debris for Materials Camps

MATERIALS

CAMP

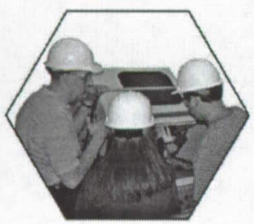
CHICAGO REGIONAL MATERIALS CAMP[SM]

A Hands-on Introduction to Materials Science and Engineering July 11-16, 2005

Who:
- Students entering their Junior or Senior year in high school in Fall 2005.
- Students involved in math, science and industrial technology classes.
- Highly motivated inquisitive learners with math and science aptitude.

Where:
- Chicago area businesses and educational institutions

What:
- Weeklong, summer camp exploring Materials Science and Engineering
- Combination of mini-demonstrations, field trips, and working in a materials lab to actively conduct a failure analysis
- A very unique team-based, problem solving science experience. Past projects have included failure of parachute harnesses, corrosion of a yacht and components in a video game system.



Cost:
- Students receive **FREE** meals, tuition, entertainment and knowledge.

How to apply:
- Applications are available on-line, and are due by **Feb 1, 2005.**
- Required information includes school transcript, a maximum of two letters of recommendation
- Personal essay (100 words or more)

Questions? For more information, please visit www.asmchicago.org or contact: Chicago Camp Coordinator, Jan Edwards. Email: jan.edwards@wiresaway.com

Sponsored by ASM Chicago Regional Chapter and ASM Materials Education Foundation

A Synopsis of the Space Shuttle Columbia Accident Investigation and Reconstruction

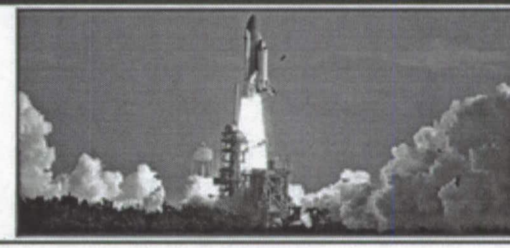
NASA

ASM Materials Education Foundation

PRESENTED BY

Steve McDanels

Chief, NASA Failure Analysis and Materials Evaluation Branch

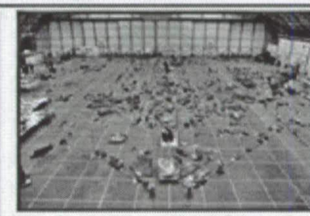


Abstract

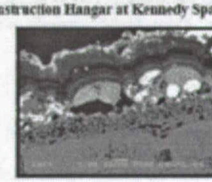
The Space Shuttle Columbia was lost during re-entry in 2003. Since the release of the original materials-related findings in August of 2003, additional testing and analysis of select pieces of debris has continued. Microanalytical techniques, including EMPA, ESCA, and x-ray dot mapping, were employed during the initial investigation; the results related the microstructural characteristics of deposit layers to the breach location in the leading edge of the left wing. Such characteristics included deposition order, composition, and distribution. The materials-related findings of the investigation will be detailed.

Biographical Sketch

Steve McDanels received his degree in Materials Science and Engineering, with a specialization in metallurgical engineering, from the University of Florida. Professional career began as a Materials Engineer performing failure analysis and crash investigations of navy and marine rotor-wing and fixed-wing aircraft. Later, transferred to the Kennedy Space Center and began performing failure analysis and accident investigations of Space Shuttle, Space Station, and ground support equipment hardware and components for NASA. Presently serves as Chief of the Failure Analysis and Materials Evaluation Branch at the Kennedy Space Center. Significant accomplishments include being awarded the NASA Exceptional Achievement Medal and serving as an editor and contributor to the American Society for Materials' Failure Analysis Handbook.



Reconstruction Hangar at Kennedy Space Center



POLISHED "SLAG" DEPOSIT SAMPLE

Event Details

Date

Wednesday June 7th
10:00—11:00 AM

Location

American Museum of Science & Energy
300 S. Tulane Avenue
Oak Ridge, TN 37830

Phone: (865) 576-3200

http://www.amse.org

Museum Admission

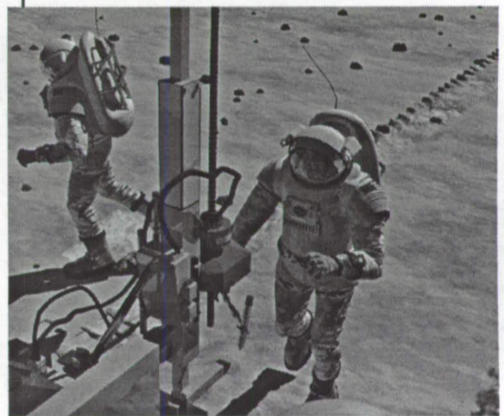
Adults $5.00
Seniors (65+) $4.00
Youth (6-17) $3.00
Children (5 and under) Free

Sponsored by: Oak Ridge Chapter of ASM International
University of Tennessee Department of Materials Science and Engineering
University of Tennessee Materials Student Advantage Chapter
Advanced Neutron Scattering network for Education and Research (ANSWER)*
*a program at UT supported by NSF

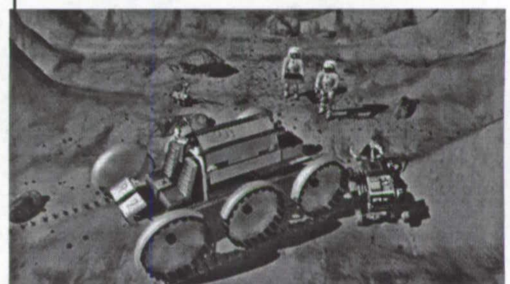
AMSE
AMERICAN MUSEUM OF SCIENCE & ENERGY

The Moon - the 1st Step to Mars and Beyond….

- Gaining significant experience in operating away from Earth's environment
  - Space will no longer be a destination visited briefly and tentatively
  - "Living off the land"
  - Human support systems



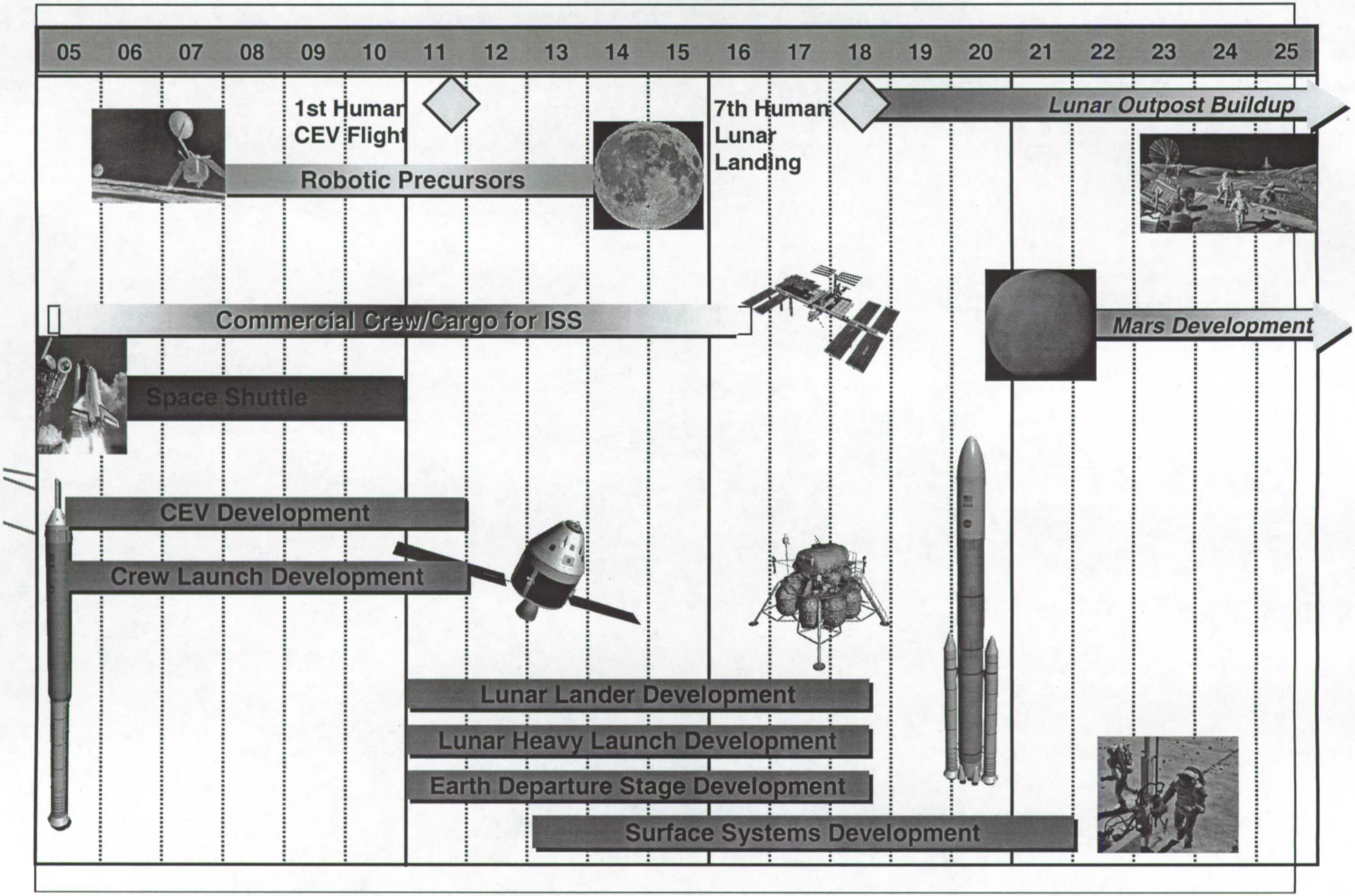
- Developing technologies needed for opening the space frontier
  - Crew and cargo launch vehicles (125 metric ton class)
  - Earth ascent/entry system – Crew Exploration Vehicle
  - Mars ascent and descent propulsion systems (liquid oxygen / liquid methane)



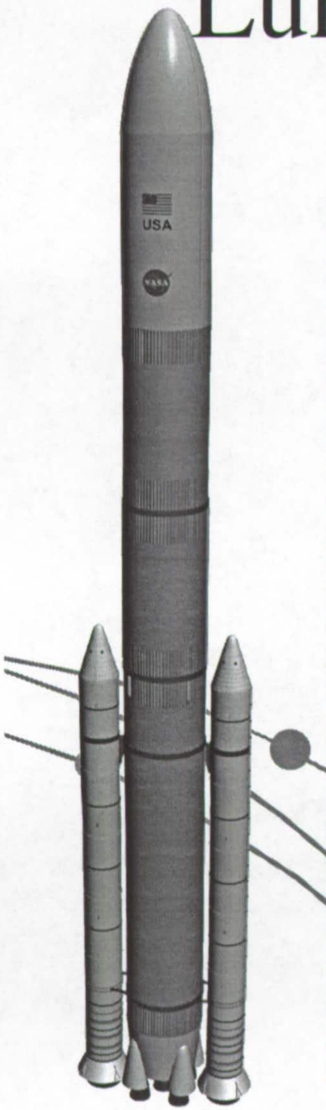
- Conduct fundamental science
  - Astronomy, physics, astrobiology, historical geology, exobiology

Next Step in Fulfilling Our Destiny As Explorers

Exploration Roadmap



Lunar Heavy Cargo Launch Vehicle



- 5 Segment Shuttle Solid Rocket Boosters
- Liquid Oxygen / liquid hydrogen core stage
  - Heritage from the Shuttle External Tank
  - 5 space Shuttle Main Engines
- Payload Capability
  - 106 metric tons to low Earth orbit
  - 125 Metric tons to low Earth orbit using Earth departure stage
  - 55 metric tons trans-lunar injection capability using Earth departure stage
- Can be certified for crew if needed

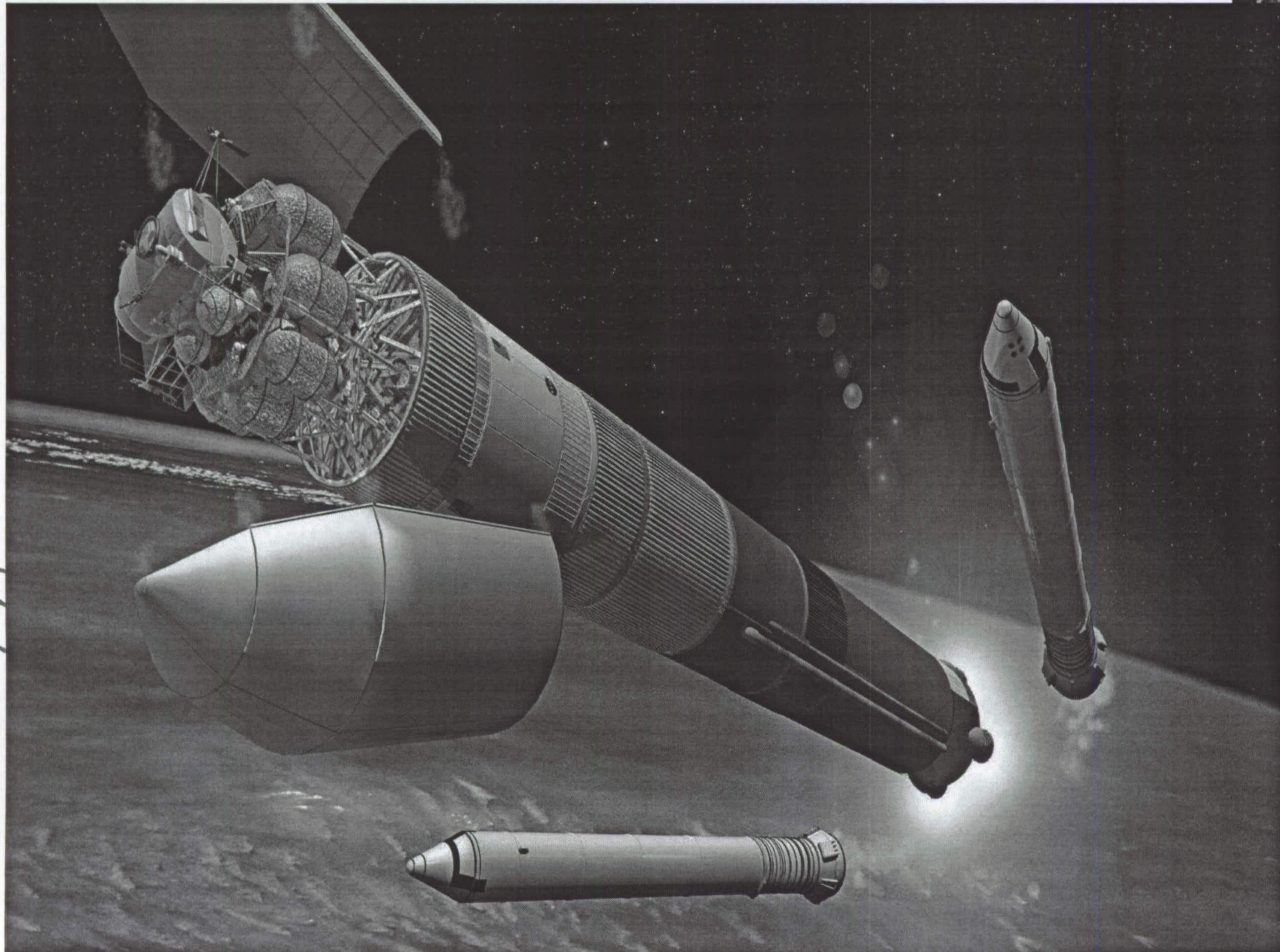
Crew Launch Vehicle

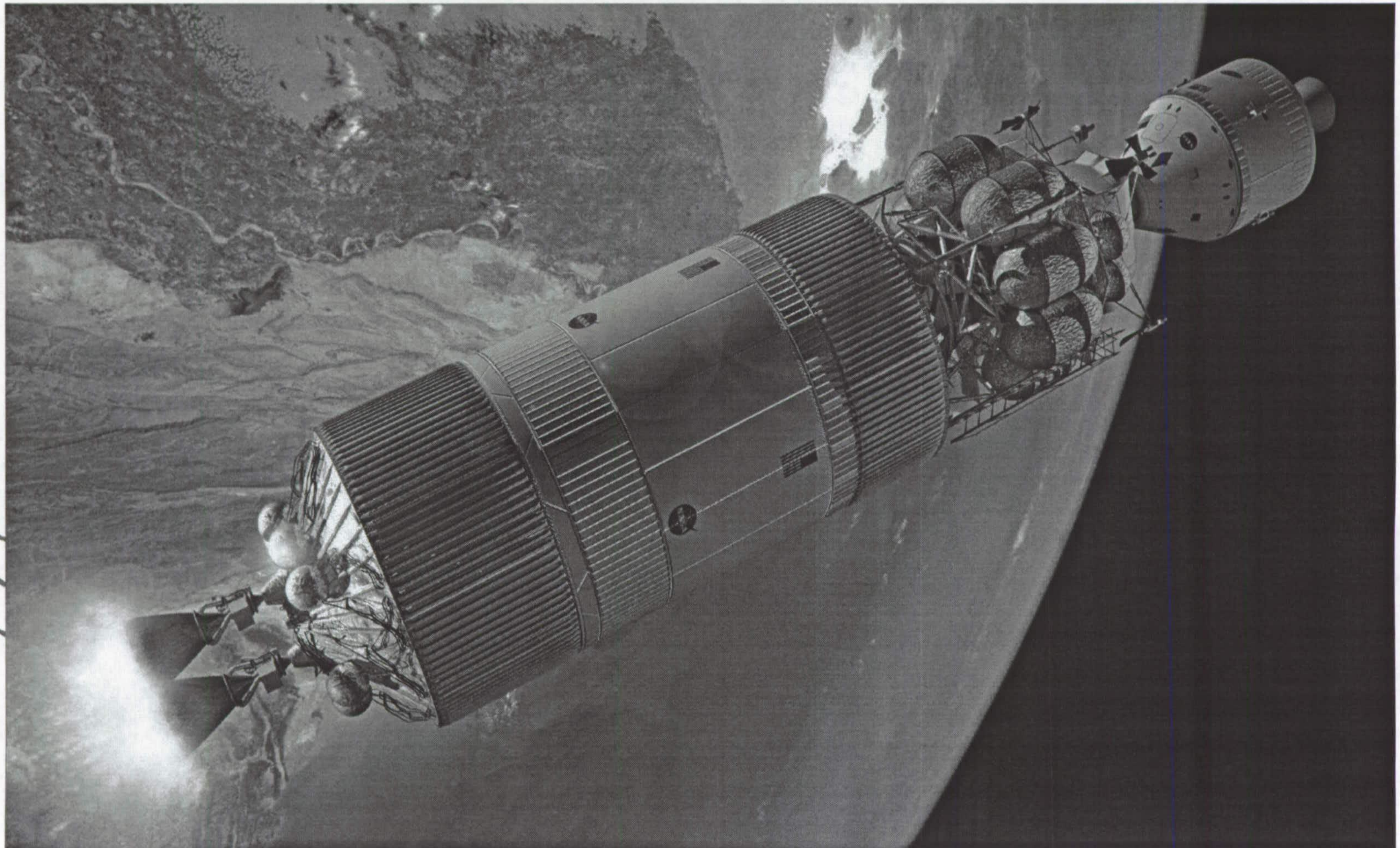
- Serves as the long term crew launch capability for the U.S.
- 4 Segment Shuttle Solid Rocket Booster
- New liquid oxygen / liquid hydrogen upperstage
  - 1 Space Shuttle Main Engine
- Payload capability
  - 25 metric tons to low Earth orbit
  - Growth to 32 metric tons with a 5th solid segment

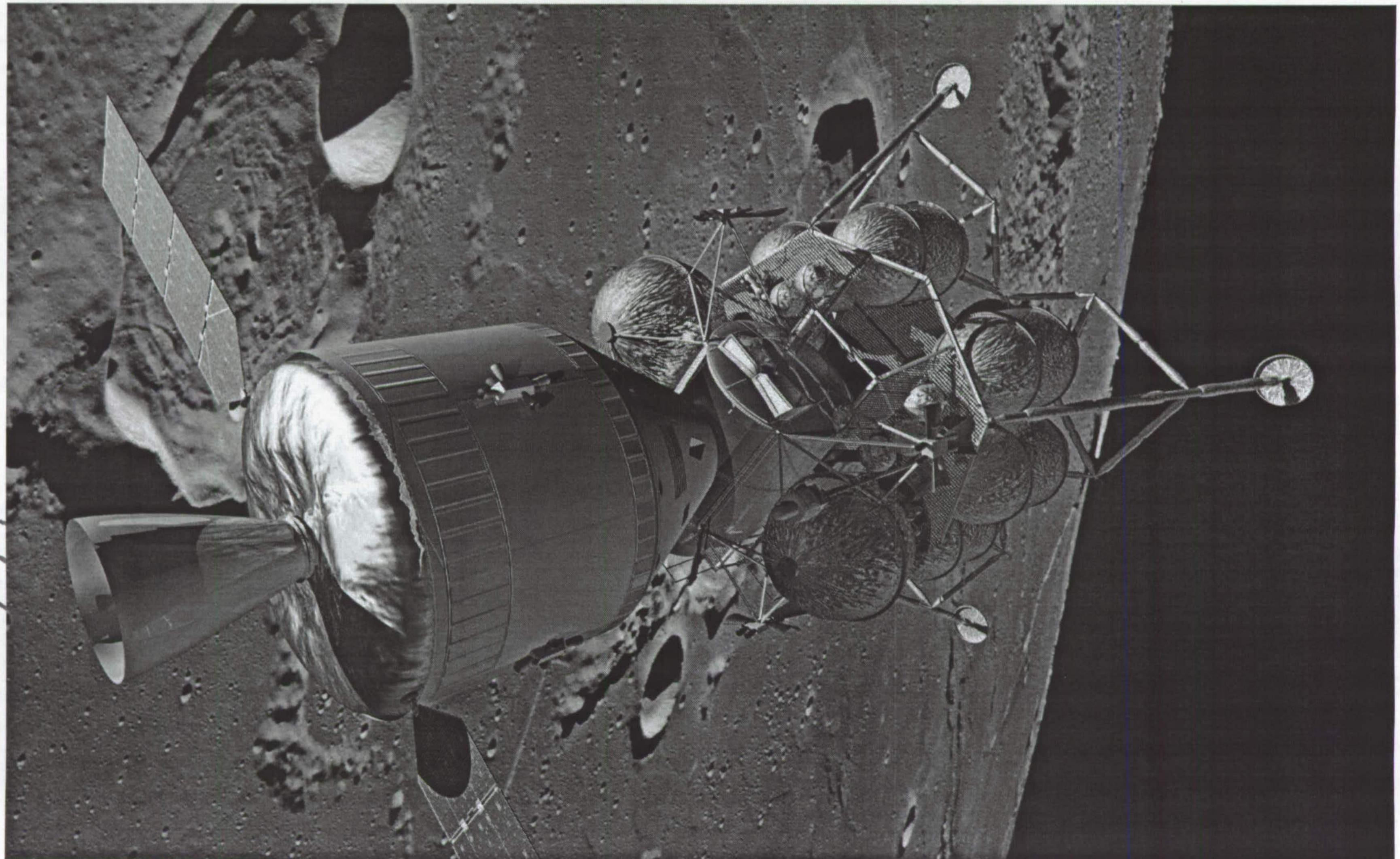
Crew Exploration Vehicle

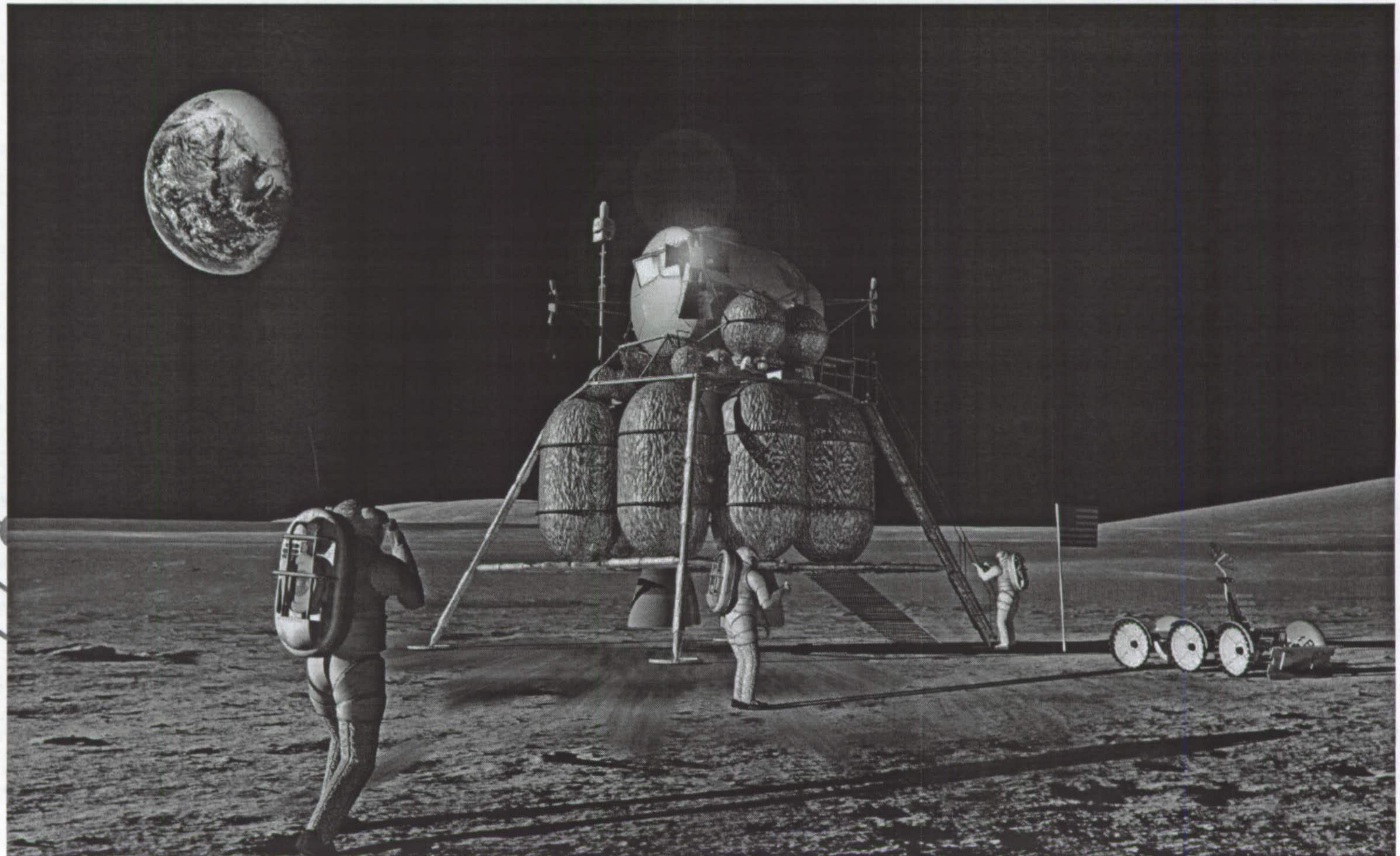
- A blunt body capsule is the safest, most affordable and fastest approach
  - Separate Crew Module and Service Module configuration
  - Vehicle designed for lunar missions with 4 crew
    - Can accommodate up to 6 crew for Mars and Space Station missions
  - System also has the potential to deliver pressurized and unpressurized cargo to the Space Station if needed

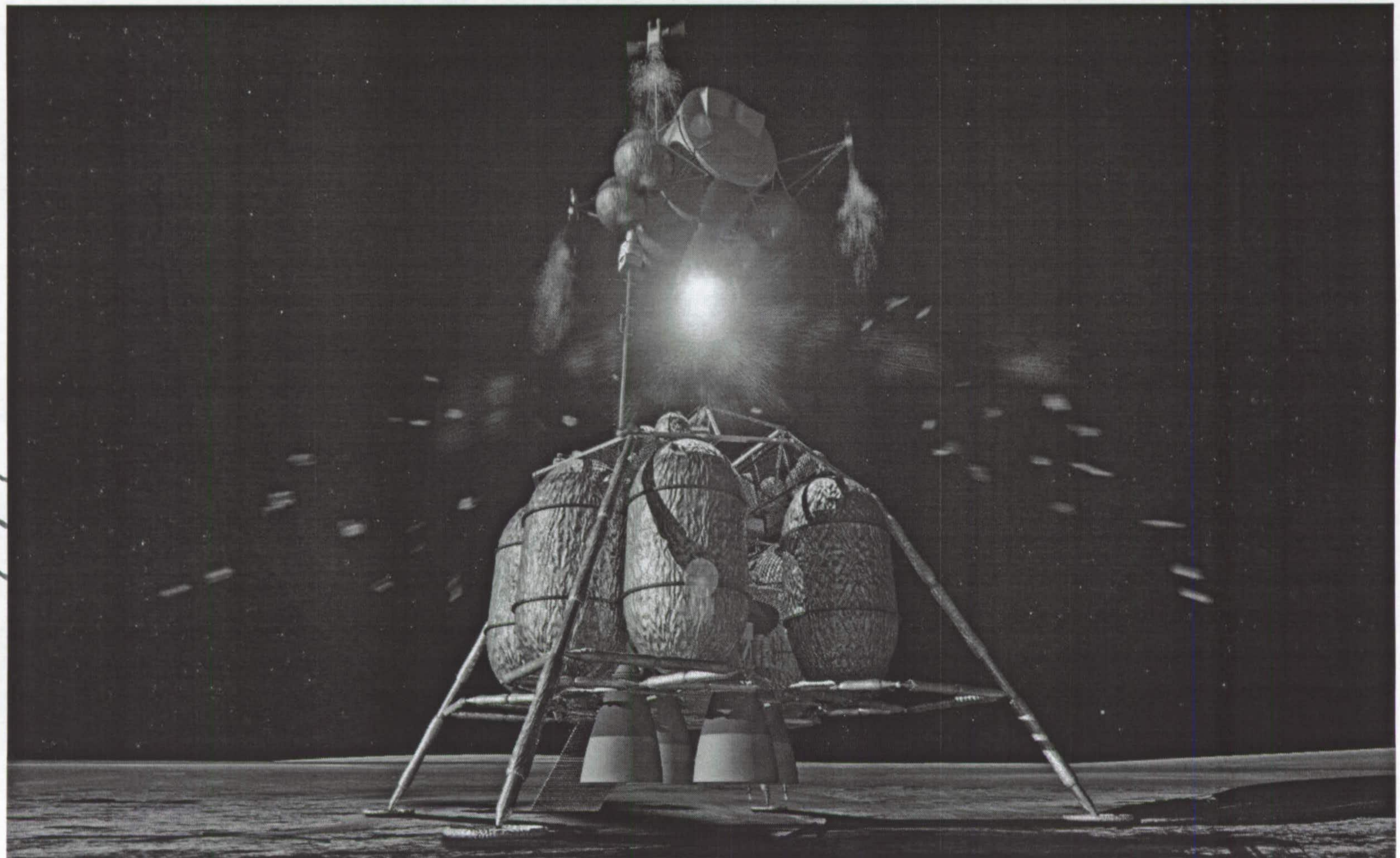
- 5.5 meter diameter capsule scaled from Apollo
  - Significant increase in volume
  - Reduced development time and risk
  - Reduced reentry loads, increased landing stability, and better crew visibility

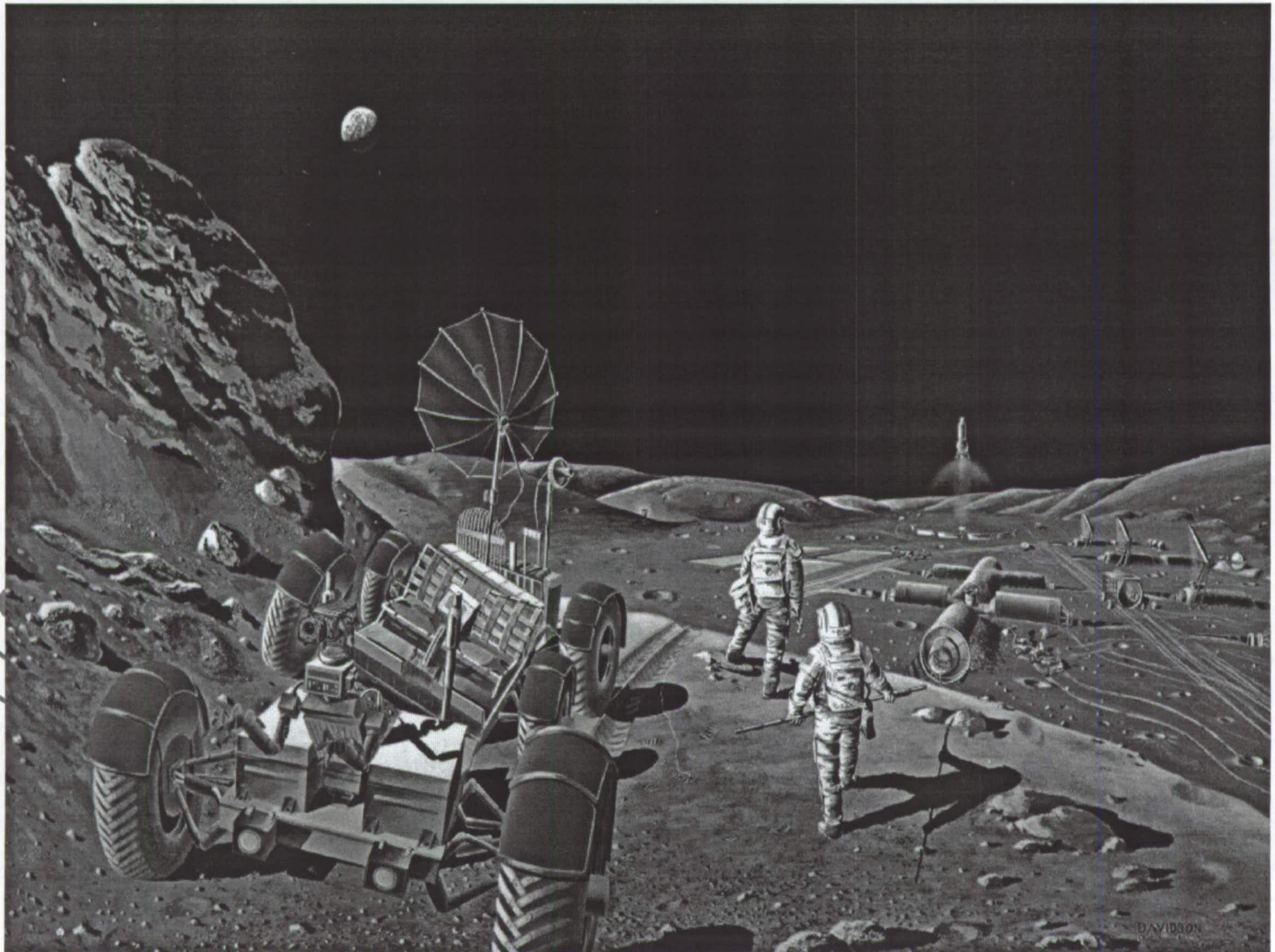











DAVIDSON